From vineyards to feedlots: A fund-flow scanning of sociometabolic transition in the Vallès County (Catalonia) (1860-1956-1999)

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Abstract:

We analyze the changes to agricultural metabolism in four municipalities of Vallès County (Catalonia, Iberia) by accounting for their agroecosystem funds and flows during the socio-ecological transition from organic to industrial farming between the late nineteenth and twentieth centuries. The choice of three different stages in this transition allows us to observe the transformation of its funds and flows over time, the links established between them, and the effect on their energy profiles. We emphasize the relevance of the integration and consistency of agroecosystem funds for energy efficiency in agriculture and their role as underlying historical drivers of this socio-ecological transition. While readjustment to market conditions, and availability and affordability of external inputs, are considered the main drivers of the transition, we also highlight the role of societal energy and nutritional transitions. An analysis of advanced organic agriculture c.1860 reveals the great effort required to reproduce soil fertility and livestock from the internal recirculation of biomass. Meanwhile, a balance between land produce and livestock densities enabled the integration of funds, with a positive impact on energy performance. The adoption of fossil fuels and synthetic fertilizers c.1956 reduced somewhat the pressure exerted on the land by overcoming the former dependence on local biomass flows to reproduce the agroecosystem. Yet external inputs diminished sustainability. Partial dependence on external markets existed congruently with internal crop diversity and the predominance of organic over industrial farm management. A shift toward animal production and consumption led to a new specialization process c.1999 that resulted in crop homogenization and agro-ecological landscape disintegration. The energy returns of this linear feed-food livestock bioconversion declined compared to earlier mixed farming. Huge energy flows driven by a globalized economy ran through this agroecosystem, provoking deep impacts at both a local and external scale.

Keywords: Energy Return On Investment (EROI) in farm systems; Integrated land-use management of agroecosystems; Sociometabolic profiles; Regional specialization; Sustainability.

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Introduction

Sustainability of agricultural systems is one of the major topics within the research on transitions towards sustainable economic systems. As it has been stated in Ecological Economics, agriculture is the most important economic sector with the potential to be a net provider of renewable materials and energy carriers to the rest of the economy (Georgescu-Roegen 1971). From a sociometabolic perspective, agroforestry and mining are two fundamental economic activities where the reproduction of society occurs as a consequence of the human appropriation of natural processes (González de Molina and Toledo 2014). The capitalist economic system challenges sustainability by relying on constantly increasing metabolic flows to support continual economic growth (Kallis 2011). While academics warn about fossil fuel and mineral resource depletion (Sorrell et al. 2010; Valero and Valero 2010), energy balances in agriculture have shown that industrial agriculture is no longer an energy supplier but a sink (Leach 1976; Campos y Naredo 1980). Moreover, agriculture has been transformed into a source of greenhouse gas emissions, water pollution and reduced biodiversity (Tilman 1999; Tilman et al. 2002; Pingali 2012; Aguilera et al. 2013). Its fundamental role within the current socio-economic systems is as a provider of cheap food, biofuels or raw materials for the rest of society. Within the framework of a sociometabolic transition towards sustainability (Haberl et al. 2011), research on agricultural metabolism is crucial in bringing to light the broader basis on which to build sustainable socioeconomic systems.

In order to understand the social and environmental driving forces that led this process, historical perspective offers a great variety of case studies in terms of edafoclimatic conditions, time periods, and social structures. This type of history is more than an isolated exercise. It can provide relevant knowledge in terms of how past organic agricultures functioned, and how their capacities and limitations related to the interplay between its social and environmental elements. Transitions to industrial agriculture went through different stages in which industrial inputs gradually supplemented or replaced human and animal labour, organic fertilizers and feed. Along the whole transition period, social, economic and environmental factors worked together, and their complex interaction needs to be deeply analysed. From a sustainability perspective, historical analysis can complement contemporary assessment of sustainable agriculture.

Even though sustainability assessment requires a wider multi-criteria analysis (Giampietro et al. 2006), Energy Returns on Investment (EROI) have been highlighted as one of the relevant indicators for this purpose (Hall 2011). Still, differences in system boundaries and methodologies render problematic the comparison among results of energy balances (Pelletier et al. 2011; Murphy et al. 2011). Some attempts have been done to agree on a coherent framework of energy analysis of agricultural systems (Jones 1989), but there is still room to establish common methods to assess the pattern of energy flows in a way that captures the complexity of agroecosystem functioning. Historical research on EROIs have revealed the relevance of internal loops of biomass flows within farm systems (Tello et al. 2016). Bringing these internal loops to light entails the recognition that agricultural practices are deeply linked with the reproduction of ecological funds, and that it is necessary to not only invest energy in obtaining “available” biomass for human needs, but also in maintaining the agroecosystem funds. Internal flows of reused biomass ensure the capacity of the agroecosystem to generate biomass in the future and maintain of vital ecosystem services (Guzmán and González de Molina 2015).

This article has both methodological and historiographical purposes. After presenting the basic features of the case study and the time points chosen in the first section, we dedicate two sections to the conceptual approach of the fund-flow energy analysis of agricultural systems and offer guidelines to implement it from a historical perspective. In addition, supplementary material with detailed information about historical sources, estimations and coefficients is provided. In the second part of the article, we present our results from a historically contextualized standpoint. First, we explain the changes to farmland and livestock dynamics over time, linking them to the ongoing historical trends. Second, we offer a detailed accounting of each energy flow to deepen the broader aggregated results previously published on this case study (Tello et al. 2016). Here we include data for a new time point from the mid-20th century, which enables us to make a more coherent historical explanation of this socio-ecological transition. Finally, we conclude by considering the social and economic drivers of this transition in the Catalan Vallès County, and focusing on the connections that linked the disarticulation of the agroecosystem’s funds with the fall of energy returns, as well as the concomitant environmental impacts that hamper the current capacity to achieve more sustainable farm systems. In a separate paper from this special issue, using the same methodology, Gingrich et al. include this case study in a broader comparison of agroecosystems in Europe and North America.

Case study

The Vallès is a small plain between the littoral and pre-littoral mountain ranges of Catalonia. The four municipalities of the study area are located 30-40 km away from the centre of Barcelona within its metropolitan region: Caldes de Montbui, Sentmenat, Castellar del Vallès and Polinyà (Map A in Supplementary Materials). As a transect area stretching from the hilltops in the pre-littoral mountains to the centre of the plain, the case study includes different types of soils and slopes with a typical Mediterranean rainfall ranging from 600 up to 800 mm a year. We have chosen three time points to illustrate the stages of socio-ecological transition: mid-19th century, which represents the case of traditional organic agriculture; mid-20th century, where there appears an incipient industrialization; and the end of the 20th century when agriculture has been fully industrialised and globalized.

Conceptual approach

We use a sociometabolic accounting of farm system energy flows, and their interaction with the underlying funds, to highlight how farmers transformed agroecosystem biophysical functioning from past organic to industrial farming and livestock raising (Giampietro and Mayumi 1997; Fischer-Kowalski and Haberl 2007; González de Molina and Toledo 2014). Our fund-flow analysis relies on the distinction set forth by Nicholas Georgescu-Roegen (1971) between funds, stocks and flows, which is particularly relevant when preindustrial and industrial farming are compared from a nature-society interaction viewpoint (Giampietro et al. 1992a and 1992b; Sorman and Giampietro 2011; Giampietro et al. 2013). A biophysical fund provides a flow, is maintained either through natural processes or through management by humans (Faber et al. 1995), and exists within a defined time span to account for a specific process (Mayumi 1991). By contrast, any non-renewable physical stock is depleted at the same rate per unit of time that a flow is extracted from it (e.g. a barrel of oil). A renewable fund cannot be exploited at any desired rate (e.g. an aquifer). Living funds are able to reproduce themselves (Faber et al. 1995), but most (such as a mule, or a farmhand) can only generate flows at a limited rate per unit of time. Furthermore, the renewal of the basic living and non-living funds of an agroecosystem, including the farm community itself, is a key aspect of its long-term sustainability (Daly 2005).

We concentrate on the main four funds of an agroecosystem, which are interlinked by biophysical flows: the members of the agricultural community, the domesticated species, and the non-domesticated species (which includes associated biodiversity and fertile soils). While the former three are living funds, fertile soils can be seen as an interface where a set of complex interactions between living and non-living components take place, behaving as an ecosystem in itself. Through historical sources we are able to estimate the characteristics of three of these funds, while farm-associated biodiversity cannot be account for solely from the energy perspective, despite its importance for maintaining many supporting and regulatory ecosystem services (Tscharntke et al. 2012). We will focus on the ability of the agroecosystem to reproduce soil fertility, livestock, and the farming community. This means that, particularly within the organic and mixed organic-industrial farming, the biomass produce tended to cover three different reproductive energy flows: manure and biomass used as fertilizers, animal feeding, and human food and fuel. Until growing amounts of external material and energy flows became physically available and economically affordable, farmers kept a careful balance between the three funds in terms of land and labour requirements. Farmers maintained these dependences and balances even under industrial farm management and breeding, although the land, labour and fossil energy carriers required for external inputs became territorially delocalized.

Within the energy accounting methodologies, this fund-flow differs from other approaches, particularly the focus on the energy return (EROI) of consumable goods compared with the energy invested by farmers from the rest of the economy. While the latter makes sense on its own right (Pelletier et al 2011; Hall 2011; Hall and Klitgaard 2012), it inevitably conceals the internal agroecological functioning within a black box. Instead of evaluating a single EROI, our approach aims at grasping a broader energy profile of agroecosystems by using several interrelated EROIs in a more complex fund-flow analysis. Although our theoretical frame is thoroughly explained in Tello et al. (2015, 2016) and Galán et al. (2016), here we summarize its main features. Final EROI (FEROI) (Eq.1) assesses the energy investment made by farmers and the society they belong to, in exchange for a basket of human consumable biomass products accounted in energy terms.

$$Final\ EROI\ (FEROI) = \frac{Final\ Produce}{Total\ Inputs\ Consumed} = \frac{Final\ Produce}{Biomass\ Reused + External\ Inputs} \qquad (1)$$

Internal Final EROI (IFEROI) (Eq. 2) assesses the portion of Land Produce reinvested in the agroecosystem as Biomass Reused (BR) in return for a unit of consumable Final Produce (FP). These flows always entail a relevant cost for farmers in terms of labour and land allocations, mainly in organic systems, also measureable in terms of energy (Guzmán and González de Molina 2009).

$$Internal\ Final\ EROI\ (IFEROI) = \frac{Final\ Produce}{Biomass\ Reused} \quad (2)$$

External Final EROI (EFEROI) (Eq. 3) relates External Inputs (EI) to the final output crossing the agroecosystem's boundaries. This ratio assesses to what extent the agro-ecosystem analysed becomes either a net provider or a net consumer of energy in its connection with the broader societal system.

$$External\ Final\ EROI\ (EFEROI) = \frac{Final\ Produce}{External\ Inputs} \quad (3)$$

Materials and Methods

Agricultural population, which we identify as *Farming Community*, can be deduced from the Population Register (1860) and Agricultural Censuses (1956 and 1999). Land uses are taken from Land Tax Records called *Amillaraments* (1860) and the Cadastral Map (1853); the Cadastral Record and Cartography [1956]; and the Agricultural Census, Cadastral Map and Satellite Digital Images (1999). For livestock numbers we used the Livestock Census (1865; 1950); and the Agricultural Census (1999). Official data was corrected when considered necessary, especially for mid-19th century (see Labour section in Supplementary Materials). Sources and estimates on crop yields and animal productivity, together with coefficients used for water content and Gross Calorific Values (GCV), can be consulted in the Supplementary Material**.**

Data on agroecosystem funds and yields provide an estimate of Total Produce (TP), which is composed of Farmland Produce (Cropland-Woodland and Pasture Produce) and Livestock-Barnyard Produce (Figure B in Supplementary Material). TP was redirected to Final Produce (FP) or Biomass Reused (BR). This distinction was assessed differently depending on the time point, under the assumption of an unavoidable dependency on local fund sustainability c.1860 that was afterwards lessened or suppressed. Accordingly, ideal conditions were set for farmland and livestock funds in order to highlight the costs of ensuring the reproduction of the agroecosystem. Biomass Reused (BR) represents the reproductive energy flows, which can be further broken down into Farmland BR (FBR) and Livestock BR (LBR). In traditional organic agricultures, BR flows were shaped by the local characteristics of farmland and livestock. On the one hand, site-specific farmland features (crop rotations, intensity, fallow) defined the biomass required to close the nutrient cycles, which in turn were highly dependent on livestock densities and management (manure availability). On the other hand, livestock densities and composition shaped Livestock BR (e.g. ruminants share). Thus, we estimate Farmland BR (FBR) and Livestock BR (LBR) through both funds' requirements. Furthermore, a balance between Final Produce (FP) and Biomass Reused (BR) needed to be reached. Reproduction of Farming Community depended on the capacity of the agroecosystem to supply an adequate amount of BR flows proportional to the quantity and diversity of Final Produce (FP) extracted from the agro-ecosystem to cover human needs, either directly through local consumption or indirectly through market exchange.

The role of External Inputs (EI) partially broke this necessary balance among different reproduction processes of the agroecosystem's funds. Since the mid-20th century, growing feed or fertilizing requirements were easily met through External Inputs (EI). Food, fuel and fibre requirements of the Farming Community were increasingly imported from outside the system boundaries, and large inputs in human labour were substituted and/or supplemented by machinery and other industrial inputs. Thus, availability of a growing range of external inputs allowed the site-specific funds' equilibrium to disintegrate, because their consistency was no longer a fundamental requirement. Methodologically, this implies changes in the hierarchical process of redirecting energy flows. We first accounted for the share of fertilizing and feed requirements provided by External Inputs, and then included what was lacking from local recirculation (detailed process and sources are provided in the Supplementary materials).

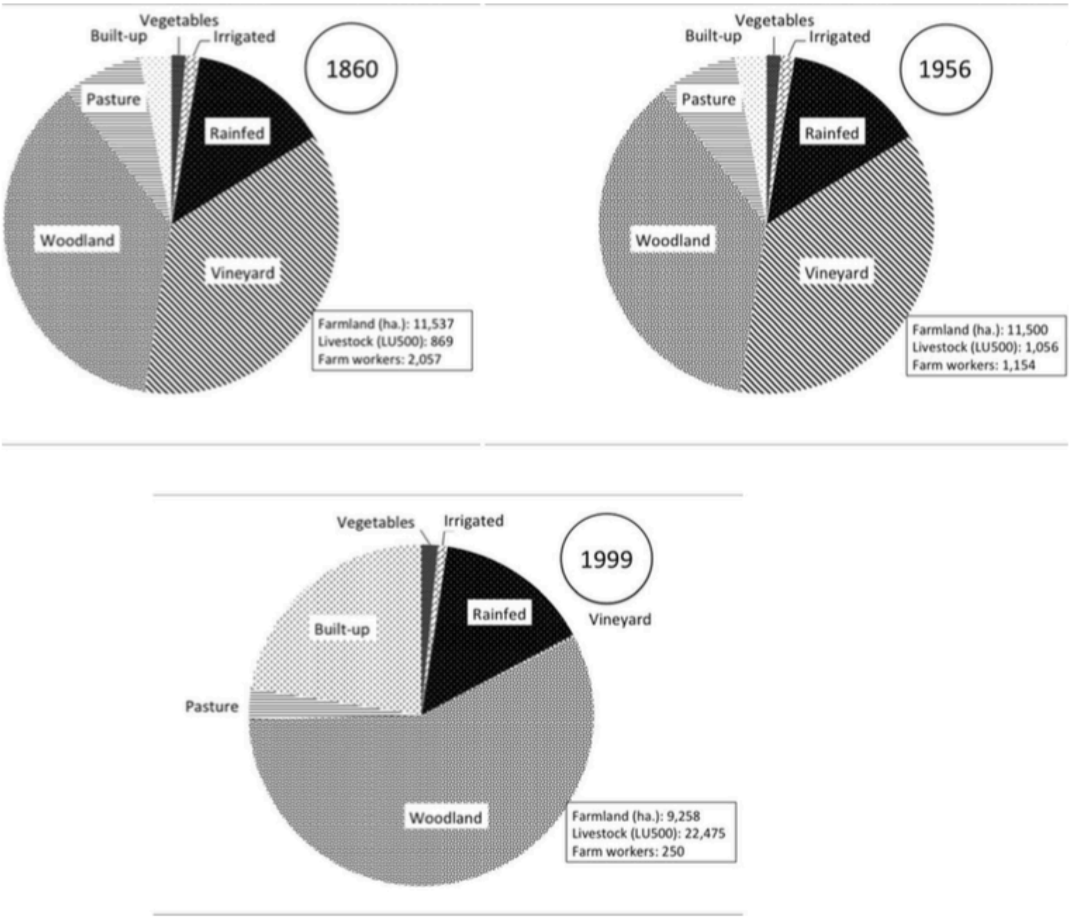
Some limitations of this research should be noted. As mentioned above, the choice of the scale of analysis hinders a more detailed assessment of possible funds erosion within preindustrial agricultures, such as soil mining. The agroecosystem scale allows us to discuss the capability of farmers to close nutrients cycles and livestock reproduction. Future research should work at the household level to evaluate if social structures, in particular social inequality, disrupted this fertilizing capacity. In the 1956 and 1999 time points, our approach requires supplementary research to capture the whole transition processes. On the one hand, changes to the global connections of the local agricultural systems (through imports and exports) resulted in an increasing externalization of unsustainability. At this point, we complemented energy assessment with other sustainability indicators. What remains within agroecosystem boundaries was also modified. When assessing energy efficiency in preindustrial and industrial agricultures, we should link them with the system's ability to meet human requirements. While Final Produce in preindustrial agricultures included fuel and building materials, lower efficiency ratios in 1999 were accompanied with a lower ability to meet human needs. We deal with both of these issues in Padró et al. (2017).

Results

Historical drivers of agroecosystem funds transformation: farmland, livestock and farming community

Cropland area decreased from mid-19th century to 1956. During the second half of the 19th century vineyard specialization colonized the territory to an extent that did not continue later on. The growing American and European demand for wine, and from 1867 onwards the arrival of the Phylloxera Plague in France, fostered vineyard expansion until the 1880s. When the Phylloxera insect destroyed all of the vines in the Vallès area, only a fraction was replanted with resistant American strains. After the plague, higher vintages obtained in the newly planted vineyards, increasingly cultivated with industrial inputs combined with the spread of winegrowing in Algerian and Greek areas, resulted in worldwide overproduction in wine markets (Pujol 1984; Planas 2007). Instead of undertaking a risky replantation of vines in poor, sloping lands many poor winegrowing tenants of the Vallès County searched for industrial jobs in the nearby textile towns (Fig. 1).

Figure 1. Features of agroecosystem's funds (% of land uses (ha))



Decline of vineyard area after the Phylloxera plague freed up space to increase pastureland from 1860 to 1956. In this period, part of the land used as vineyards, mainly in the steepest areas, was given over to barren land or brushwood classified as potential pastureland. By 1956, smaller areas of abandoned vines had turned into forests. The decrease in vineyards and olive groves was partially offset in 1956 by an increase in the area allocated to rainfed cereals, legumes and potatoes. After the downturn of wine prices in 1931, and the increase in grain prices from 1936 onwards, wheat and barley crops expanded (Llobet 1968). The severe food shortages during the Civil War, along with the autarkic years of Franco's dictatorship, may well explain the increase in cereal-growing areas observed in 1956 (Infante-Amate et al. 2015). Population growth and dietary transition shaped the agricultural landscape. During the first decades of the 20th century, the growing meat and milk demand from cities like Barcelona and other nearby industrial towns (Pujol 2002; Pujol et al. 2007; Nicolau and Pujol 2004) offered an opportunity to shift from vineyard to livestock specialization (Planas 2003). This inaugurated a shift towards a greater share of feed-oriented crops, from 13.7% in 1860 to 26.4% in 1956.

The abandonment of extensive livestock rearing, and woodland extractions for fuel consumption, led to the huge increase in woodland area in 1999 (Marull et al. 2015; Cervera et al. 2016). Together with the loss of former landscape mosaics, because of the disappearance of pasture and the integrated land-use management of farms, and the construction of linear infrastructures (roads, power lines), ecological connectivity dropped between 1956 and 1999 (Marull et al. 2010; Marull et al. 2016). Indeed, during the second half of the 20th century built-up area hugely increased, permanently replacing agricultural land—mainly of the best quality (Tello et al. 2014). Urbanization and infrastructure development destroyed up to 47% of soils of high agronomic value (Olarieta et al. 2008). In 1999, woodland and built-up areas covered 80% of the total area. At this point 71% of total cropland area was allocated to animal-feeding crops, including barley and fodder. Areas of wheat cultivation decreased by 88%. In spite of their site-specific traits, the main trends of this case study correspond to the paths of Spain (Infante-Amate et al. 2015) and Europe more generally. At the global scale, just over 10% of the grain harvested was fed to animals in 1900.That number rose to 20% by 1950, and attained about 45% in the late 1990s (Smil 2000; Fischer-Kowalski and Haberl 2007). Higher meat consumption has been pushing through an increase of livestock densities, which are reached by the intensification of livestock feeding practices.

Livestock density c.1860 (7.2 Livestock Units 500/km^2 of farmland area) was relatively low compared to contemporary European and American averages (Fischer-Kowalski and Haberl 2007).[1] Average values in intensively cropped Austrian villages in 1829, or in the American Great Plains during the late 1880s, reached 25 Livestock Units 500/km^2 of farmland area (Cunfer and Krausmann 2009, 2016). Yet the very low livestock density was cosistent with the high population density the low availability and natural productivity of Mediterranean pastures. This involved a highly intensive organic farm system where animal feeding competed with human food, and where vineyard specialization lessened to some extent the draft power required to toil the land. Draught animals predominated, followed by meat-, wool- and cheese-producing animals, and small domestic animals (Figure A in Supplementary Materials). This composition responded to the multifunctional role of livestock in these pre-industrial agricultures (Krausmann 2004), which provided traction, manure, food (meat, eggs and milk), fibres (wool and leather) and heat when stalls were placed near or under farmers' homes. Smaller draft power animals like donkeys and mules, well adapted to plough vineyards, predominated. They were fed mainly with cropland by-products and pastures, a feeding pattern that reduced competition of animal breeding with human food consumption.

During the European agricultural crisis at the end of the 19th century, and following the expansion of industrialization, agricultural wages rose (Garrabou et al. 1991 and 1999). On the one hand, a decline in manpower demanded an increase in draft power, which explains the increase in the number of horses in 1956. On the other hand, the rise of wages increased the demand for animal produce (Pujol 2002). The beginning of livestock specialization in the Vallès, mainly for milk and meat products sold to Barcelona and other industrial cities and towns (Planas 2003), led to the increase in cattle in 1956. Together with the larger cattle population, a shift in cattle breeding also took place. The change from bovine used for draught power to dairy nutrition and meat production required imports of more productive breeds (Pujol 2002). Both horses and new bovine breeds needed to be fed with better quality products. At the time, oats, barley and fodder were suitable for feeding horses, and these were complemented with wheat crops used for human

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[1] Livestock Unit 500 is used to standardize livestock weight, and is calculated adding the total live weight of the livestock and dividing it per 500 kg.

consumption. Livestock feed began to compete with human food for land, instead of relying to a large extent on by-products as had previously been the case.

In 1999, specialization in livestock production had already reached its peak in the Vallès. At that time, the greatest share of livestock were bred and raised in feedlots for industrial processing. Livestock densities multiplied by 26 and its composition changed tremendously. Working animals disappeared and livestock breeding was totally focused on meat production, particularly pigs. This change can be mainly explained by the increase in meat consumption, which reached its highest point in the late nineties (Marrodán et al. 2012), but also by the concentration of the meat industry in particular regions. The Vallès is not, however, considered to be a Catalan county well-known for specialised meat production, such as Vic where livestock densities are over 907 Livestock Units 500/km^2 (IDESCAT 2009). The predominance of monogastrics which, on the one hand, have a higher Feed Conversion Ratio (FCR) also entailed, on the other hand, higher grain requirements. Indeed, as part of the shift from working animals to meat production, ruminants experienced a nutritional transition: only 17% of them were fed with grains in mid-19th century, compared to current rates ranging from 67 to 85% of animal diets. These patterns of feeding, richer in cereal and legumes, compete with food crops for land and water (Naylor 2005). Furthermore, the animal feed production in the study area could not meet the huge new requirements, and needed high imports from other countries (Padró et al. 2017).

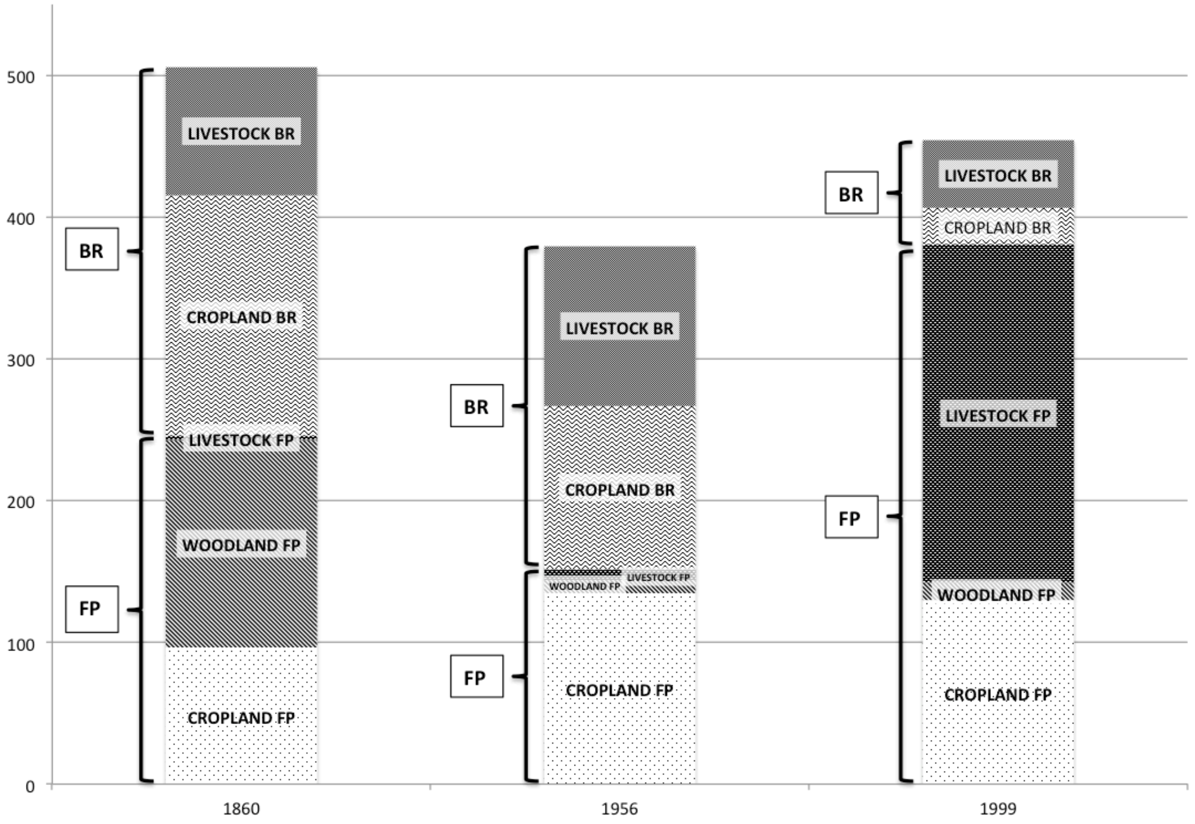
Population density almost doubled over the first period analysed (1860-1956), and tripled over the second period (1956-1999). This explains the growth in urbanized areas and those devoted to new industrial sites, together with the socio-political changes to city planning (Parcerisas et al. 2012). Likewise, the active agricultural population decreased throughout this period. Mechanization, better job conditions, and the crisis in agricultural labour of rural areas of developed countries caused by globalization may explain this decrease. Together with labour decrease the overall installed power grew along three well-differentiated patterns. The installed power in all sorts of biological and mechanical converters (cows, mules, horses, human agricultural workforce, tractors) grew from 449 kW to 780 kW between mid-19th century and 1956, while it was nine times higher by 1999 (7,342 kW). In 1860, humans performed 46% of farm work, while the remaining 54% of the work was done by animals. In 1956, manpower (14%) still coexisted with draft power (39%) and machinery (47%). By 1999, however, manpower had totally disappeared.

Flows: from organic to industrial farm systems; from cyclic to linear structures

The energy content of Total Produce (TP) decreased 25% from 1860 to 1956, from 42 to 33 GJ/ha of farmland. This was the result of several factors: (i) a much lower extraction rate in woodland (from 41 to 21 GJ/ha); (ii) the decrease in cropland area; and (iii) the post-Phylloxera loss of vineyards, a very productive crop in energy terms because of its woody by-products. Thus, the agroecosystem in 1956 was somehow subject to less human pressure. Although the human ecological load was partially relaxed within the whole farmland area, cropland area performed differently, and higher cereal productivity resulted in an increase in total harvest from 46 to 54 GJ/ha of cropland. Despite this intensification process, the effect of reduced cropland area caused Total Cropland Produce to decrease within the period (Fig. 2).

In 1999, Total Produce (TP) increased again, coming close to mid-19th century levels, but with a very different composition. Exponential growth in Livestock-Barnyard produce substituted for the sharp reduction of Woodland Produce. Woodland area strongly increased and livestock grazing practically disappeared. Farmers produced an energy output similar to that in 1956 even though cropland area was halved. As a result, Total Cropland Produce increased to 93 GJ/ha. At this point, 90% of Land Produce came from cropland, which only represented 20% of the whole territory. By comparison, this ratio was 70-40% in 1956 and 60-50% c.1860. Farmers concentrated their pressure in the reduced cropland area, and reduced it almost entirely in woodland and pastures. Livestock feedlots also intensified biomass production within the territory. Therefore, we observe a polarization on human disturbance depending on the land use (Marull et al. 2016).

Figure 2. Composition of Total Produce (TP) between Biomass Reused (BR) and Final Produce (FP) (TJ)



The Vallès County energy transition, which entailed a long-run abandonment of woodland extraction and an intensive adoption of fossil fuels for domestic and industrial uses (Carpintero 2005; Rubio 2005), combined with the human nutritional transition, largely explain the changes in FP composition. Firewood and timber, together with vineyard and olive woody by-products, constituted 84% and 56% of FP in 1860 and 1956 respectively. In 1999 woody biomass only represented 9% of the FP. At the same time, animal produce grew from 1% to 3%, and then to 76% of FP. In terms of human needs, until the second half of the 20th century, the composition of Final Produce met both food and fuel requirements of the local population. In the late 20th century, the agroecosystem was unable to cover these needs, now supplied from external territories through imports that embodied a great consumption of fossil fuels. On the other hand, food produce was no longer oriented to meet local or regional demand but was delivered instead to the rest of Spain and Europe (Padró et al. 2017).

In preindustrial agricultures the role of Biomass Reused (BR) was mainly to close the nutrient cycles, either directly when applied to cropland as buried fresh biomass or burnt *formiguers*, or indirectly through livestock feeding and bedding. This required a complex, multiple use and close integration between land-uses and animal husbandry aimed at maintaining both soil and livestock funds. These looping energy flows entailed a relevant cost in biophysical terms: 48% of TP c.1860 was redirected as BR, 38% in 1956, and 31% in 1999. Although these changes in BR shares appear small (in line with the stability of Biomass Reuse throughout the sociometabolic transition found in other case studies) (Gingrich et al. this issue), its role was absolutely transformed. Synthetic fertilizers and the easy access to imported feed in global markets meant that BR played a much larger role in 1999 than it did in the 19th century. While c.1860 60% of biomass reused were put directly back into the land (Cropland BR), only 9% were in 1999 and the rest went to feed animals (Livestock BR). Even within Livestock BR, livestock feeding changed from taking advantage of many by-products and natural pasture grazing to become the main recipient of grains and fodder. BR flows were responsible for the sustainable reproduction of agroecosystem funds c.1860. In 1956, soil fertility was partially reproduced through external inputs, while livestock was mainly fed with local biomass. In 1999, BR was not capable of reproducing soil fertility or livestock-barnyard needs, which became highly dependent on external inputs.

In 1860, all External Inputs (EI) had an organic origin, more than 50% of which were endosomatic (30% labour, 20% humanure, and 50% domestic residues). At that time, EI represented 5% of the Total Inputs Consumed (TIC). Conversely, in 1956 endosomatic and organic inputs accounted for only 7% (5%

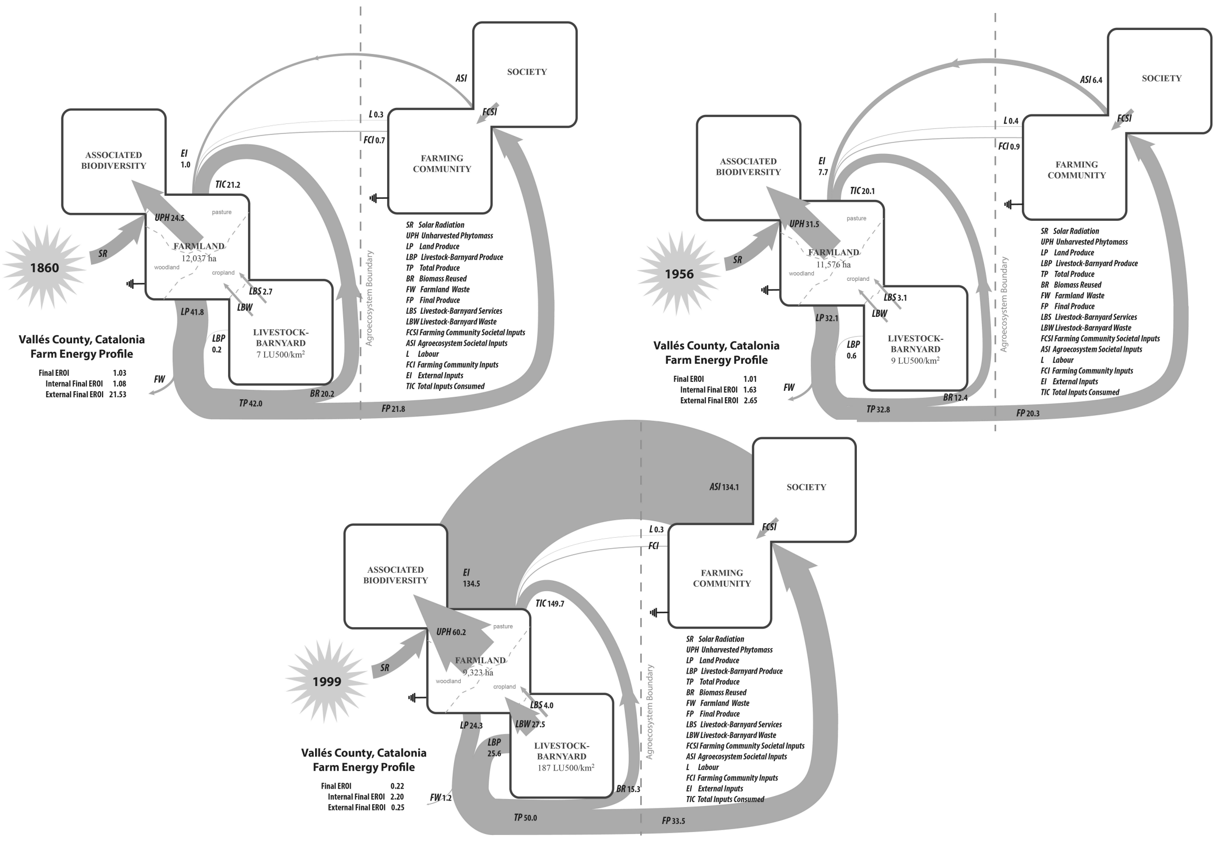
labour, 2% humanure) and 17% respectively, while 83% came from outside and were almost exclusively non-renewable in origin, mainly synthetic fertilizers but also machinery. At that point, EI accounted for 37% of TIC. In 1999, EI came almost entirely from outside the agroecosystem's boundaries (humanure and domestic residues were no longer reused, and labour was only 0.3% of EI), and represented 90% of the TIC. The biomass component of these EI constituted nearly 76% of the total, almost all of which was animal feed. The huge amount of feed imports partially hid the increase of EI due to agricultural mechanization, which increased three-fold from 1956 to 1999. Unlike other similar research on agricultural metabolism where synthetic fertilizers and machinery represent the largest energy consumers (Pelletier et al. 2011), livestock specialization in Vallès County reflects the disproportionate relevance of biomass external inputs within industrialised agroecosystems. Biomass flows increased 62-fold in the last fifty years (Mayer et al. 2015).

EROI analysis

Final EROI (FEROI) decreased steadily throughout the period 1860-1999, and more rapidly from 1956 to 1999 (Fig. 3). Although both Final Produce (FP) and Total Inputs Consumed (TIC) increased through the whole period, the increase in TIC (+1,140,832 GJ) was much higher than the increase in FP (+49,484 GJ). In spite of the intensive energy requirements of preindustrial fertilizing techniques in the Vallès study area, both FEROI and Internal Final EROI (IFEROI) were higher than 1. The slight decrease of Final EROI (FEROI) between the mid-19th and mid-20th century was led by a higher decrease of FP compared with the decrease in TICs. The reduction of woodland extraction affects the FEROI, but does not imply an explicit decrease in energy efficiency. Farmers substituted local and renewable fuel sources for external and non-renewable ones. Changes in soil fertilization practices explain the shifts in the nature of the inputs required to maintain the nutrient balance. In 1956, the introduction of synthetic fertilization, which increased external inputs (+60,000 GJ) was accompanied by a decrease in Biomass Reused (-115,000 GJ). Therefore, the energy requirements to replenish the nutrients through traditional, intensive biomass fertilizing techniques, especially *formiguers* (which used woody biomass), were higher than those of synthetic fertilizers. This sets a sharp contrast with the strong fall of energy returns found in 1999, when much higher quantities of synthetic fertilizers almost entirely replaced organic ones. Cropland biomass reused came mainly from cropland by-products, while synthetic fertilizers required huge amounts of non-renewable energy. Thus, the implications in terms of internal-external sustainability should be addressed in a more detailed way.

Figure 3. Energy profiles of Main Funds, Flows* and EROIs of the farm systems studied c.1860, 1956 and 1999

*Flows are expressed in relative terms (GJ/ha of farmland)



The increase of IFEROI from 1.13 to 1.65 between 1860 and 1956 shows the effect of the abandonment of this effort to recycle biomass. Nevertheless, considering separately Land and Livestock processes, changes to funds' structures had different effects on IFEROI. On the one hand, higher livestock density increased BR to feed meat and dairy cows that provided a smaller amount of FP exerting a downward pressure on IFEROI values. On the other hand, reduction of animal draft power lessened a share of BR that did not provide anything to FP exerting an upward trend on IFEROI values. As a result, the abandonment of traditional fertilizing methods led to a higher internal energy efficiency in Cropland [Internal Cropland EROI: Cropland Final Produce/Cropland BR], which increased from 0.62 to 13.07. At the same time, Internal energy efficiency of Livestock bioconversion [Internal Livestock EROI: L-B Final Produce/L-B BR] increased only to a lesser extent (from 0.03 to 0.05). In the end, the combination of all these countervailing trends—including the reduction of forest extraction in FP which required no BR flows—resulted in an IFEROI increase.

From 1956 to 1999, the increase of TIC was 7.6 times higher than the increase in FP. The share of EI, which rose from 37% to 90% of TIC, drove this increase. FEROI was shaped mainly by EFEROI in 1999. The energy profile in 1999 is closely linked to livestock specialization. The increase in Livestock Final Produce led the increase in FP and the huge increase in EI was driven by the amount of Livestock External Inputs. Thus, the low final energy efficiency is mostly explained by the low energy efficiency of livestock bioconversion. Although the animal Feed Conversion Ratio (FCR) raised during this period, feed requirements entailed a large amount of BR and a huge quantity of feed imports.

In addition, land-use changes may also provide an explanation for the lower returns on investment for industrial compared with organic agricultures (1860-1999). FEROI efficiencies on dry cropland, irrigated and vineyards ranged from 0.4-1 to 0.2-0.3, while the greatest decline was due to the energy transition in forests where FEROI dropped from 47.7 to 1.4. In the same vein, EFEROI experienced an order of magnitude decrease from 2.2-3 to 0.2-0.3 in cropland uses. Despite an increase of 90% in FP, the energy efficiency is lower in irrigated than in rainfed areas because of the diminishing returns on TIC. Here a 1.9-fold productivity increase meant a 2.6-fold growth in BR.

Figure 4 plots the different profiles of FEROI of the three time points analysed within the conic surface that represents all the possible relationships that exist between FEROI, IFEROI and EFEROI according to the following equation:[2]

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

The set of relationships among FEROI, IFEROI and EFEROI shifted from 1860 to 1956 towards two contrasting regions of the three-dimensional surface in Figure 4 (left). The high EFEROI combined with a comparatively lower IFEROI led to the Final EROI of 1.08 attained in 1860 thanks to a strategy of Low External Input Technology (LEIT) (Gliessman 1998; Tripp 2008). IFEROI was much lower than EFEROI because of the strong recycling effort that was the only feasible strategy to maintain high productivity in the absence of synthetic fertilizers or machinery. In 1999, when an industrial farming strategy fully adopted synthetic fertilizers instead of using *formiguers* and of machinery instead of maintaining work animals, EI replaced BR. As a result, the LEIT organic and the industrial strategies generated two opposite patterns (Tello et al. 2016). The 1956 point remains in between, although nearer to an industrial rather than a LEIT pattern. Interestingly, in this organic-industrial middle ground, the direction of optimal improvement according to equation (1) shown in Figure 4 (right) points towards keeping proportional amounts of BR and EI—that is, following the diagonal of 45° where $\frac{BR}{EI} = 1$, leaving only little room to substitute BR with EI. The full industrialization of meat production in feedlots followed a completely different path than the optimal vector seen in 1956. The general change in energy patterns seen in Figure 4 was mainly driven by the ratio $\frac{BR}{EI}$, which shifted from $\frac{242{,}864\ GJ}{12{,}210\ GJ} = 19.9$ in 1860 to $\frac{144{,}009\ GJ}{88{,}745\ GJ} = 1.6$ in 1956, and to $\frac{142{,}246\ GJ}{1{,}253{,}660\ GJ} = 0.1$ in 1999.

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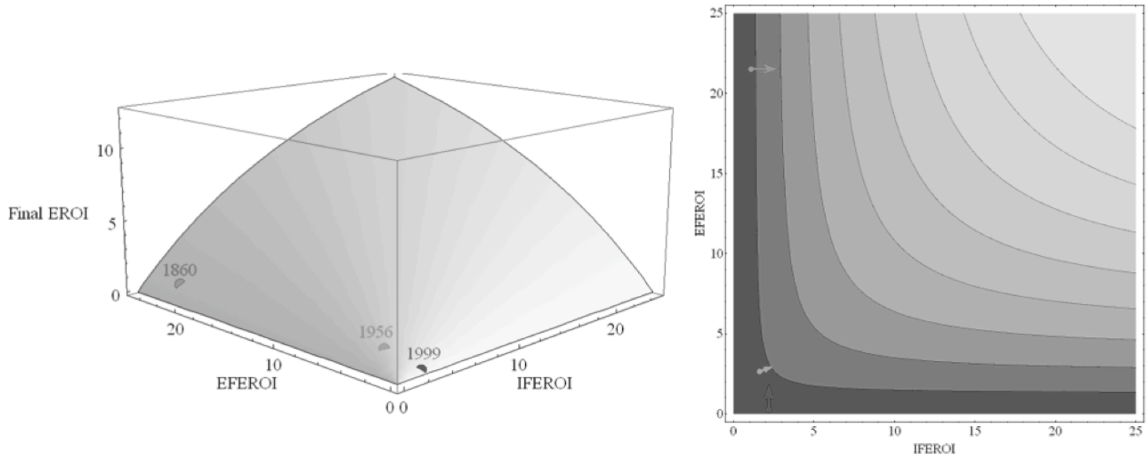
[2] By definiton, $\frac{EFEROI \cdot IFEROI}{EFEROI + IFEROI} = \frac{\frac{FP}{EI} \cdot \frac{FP}{BR}}{\frac{FP}{EI} + \frac{FP}{BR}} = \frac{\frac{FP^2}{EI \cdot BR}}{\frac{FP\ (BR+EI)}{EI \cdot BR}} = \frac{FP}{EI+BR} = FEROI$ (Tello et al. 2016)

Figure 4. Graphical representation of Final EROI as a function of EFEROI and IFEROI (left), and the directions and comparative lengths of the potential improvement of Final EROI by changing EFEROI-EFEROI combinations at any point (right), in the farm systems of the Catalan study area c.1860, in 1956 and in 1999.



Discussion

Why the fund-flow nexus matters

Through the sociometabolic scanning of the agroecosystem energy functioning in the Vallès County c.1860, 1956 and 1999 we have identified three very different energy profiles in the composition of basic funds and the pattern of energy flows. Our results highlight that changes in agroecosystem energy efficiency cannot be explained only by a different distribution of flows, but also by the ongoing change in the composition of funds. Therefore, the fund-flow scanning methodology is a useful tool to explain how the energy performance of an agro-ecosystem is strongly related to structural change in their underlying funds. Only when energy efficiency analysis links the pattern of flows with the change in funds composition and integration, can it provide useful insights for a sustainability assessment of agricultural metabolism. First of all, energy flows are strongly influenced by the amount of woody biomass circulating in the agroecosystem. The functions of forests as an integrated element, as well as of woody crops, strongly influence energy efficiency indicators. Conversely, higher livestock densities require greater amount of inputs (biomass flows coming either from the local boundaries or from other agroecosystems) per unit of final product obtained, thus lowering energy returns. Second, although elements outside the structure of funds, such as synthetic fertilization, became increasingly important, the relationship between livestock density and agricultural area allows us to better understand both the higher final efficiency of the integrated pre-industrial agroecosystems, and the low efficiency of an industrial model of livestock breeding adjoined to a (mainly abandoned) territory.

By focusing our energy scanning on the role of funds, we also observe how specializations in an advanced organic or an industrial agriculture behave quite differently, mainly due to contrasting scale-dependence. Before the Green Revolution and global trade expansion, even if a significant part of the agro-ecosystem was already market-oriented, there were biophysical limits that could not be broken without opening metabolic rifts in the replenishment of soil nutrients or animal feeding. Preventing these rifts entailed hard labour and land investments, which were overcome through the socio-metabolic transition towards mechanical and oil-dependent inputs. In 1956, we observe an intermediate organic-industrial farm system increasingly oriented towards livestock raising and dairy products, that gave way to slightly lower energy returns, particularly with respect to external inputs.

Yet it was not until the end of the 1960s when the farm system underwent a complete industrialization that totally changed the energy profile. Mechanization of agriculture and the use of synthetic fertilizers and biocides on cropland underwent astonishing growth rates. In Spain, the consumption of fuel doubled between 1954 and 1959; lubricating oil increased by 126%; electricity by 70%; synthetic fertilizers by 64%; and tractor power capacity by 111%, and another 150% between 1959 and 1963. Feed imports, almost non-existent in 1956, grew more than six-fold between 1957 and 1963 at a yearly rate of 36.4% (Ministerio de Agricultura 1954, 1959 and 1963). In 1956, the Green Revolution was only just beginning, which explains why the energy performance was not radically different from that of c.1860. A similar trend is also found in forest abandonment, which was also just beginning. Although forest area increased slightly due to vineyard abandonment, forest extraction decreased overall. This trend was exacerbated later on, when the arrival of gas bottles in urban households of Catalonia marked the end of charcoal making.

It is noticeable how preindustrial organic agricultures, like the one in the Vallès County c.1860, managed to be energy efficient in spite of the high energy investment needed to maintain their funds. On the one hand, the low livestock density and lack of manure led to a costly investment in labour-intensive alternative fertilizing methods (Olarieta et al. 2011; Tello et al. 2012). On the other hand, the unavoidable dependence on livestock to obtain draught power and manure involved large bioconversion losses. These two heavy burdens were offset to some extent by the multiple and integrated uses of land and livestock. Thanks to that, they were able to attain energy efficiency ratios above 1, only slightly higher than the mixed organic-industrial farm system in 1956, but much higher than the agroindustrial system in 1999. What stands out is that past organic farm systems were able to override all these partial inefficiencies, which in a solar, areal-based energy system inevitably involved a high land cost (Guzmán and González de Molina 2009), by taking advantage of many synergic linkages between funds through land-use efficiency (Marull et al. 2016; Padró et al. 2017).

Multifunctional uses of livestock and arboriculture combined with cropland-livestock integrated management, were two sides of the same coin. Thanks to the multipurpose character of vineyards and olive groves, the energy flowing from them was able to cover simultaneously diverse human biomass requirements (food and fuel) and animal feeding (e.g. green shoots, leaves). Livestock, in turn, provided draught power and manure besides meat and dairy products. In the same vein, using crop by-products (straw, stubble, husks, brans, and oil and grape pomaces), combined with natural pastures to feed livestock, partially reduced the competition of animal bioconversion with human nutrition. All these looping fund-flow linkages established through land-use integrated management led to complex landscape mosaics, where the production of cash crops such as wine were combined with other biomass flows oriented to sustain the reproduction of three basic funds of the agroecosystem: human nutrition, soil fertility and livestock feeding. This gave way to heterogeneous landscapes where peasants exerted different spatial levels of disturbance, which in turn gave rise to a higher habitat differentiation for a rich farm-associated biodiversity able to perform vital ecosystem services (pollination, control of plagues and diseases, clean water, etc.) — that is, it allowed for the maintenance of another vital fund of the agroecosystem (Marull et al. 2016). This fund-flow internal complexity, and the corresponding mosaic pattern of cultural landscapes, was kept in a context of vineyard specialization that was still compatible with a local sustenance-oriented agricultural and livestock management.

Since the first decades of the 20th century certain driving forces started changing the farm system. First, the introduction of small amounts of synthetic fertilizers allowed farmers to reduce Cropland BR, which entailed a lower energy cost to the agroecosystem's fund maintenance. The introduction of machinery was still scant in 1956, and was accompanied by a replacement of mules with horses. The end of transhumance and the diffusion of industrial animal fattening in feedlots put an end to extensive grazing in pastureland and open woods. Urbanization increased dairy products and meat intake, leading to a deep nutritional transition away from the highly praised Mediterranean diet, and fostered the increase of livestock densities in the Vallès area. The energy transition towards fossil fuels entailed a deep turnaround in the fund-flow complexity kept so far. The widespread use of cheap domestic fossil fuels, like gas cylinders and, later, natural gas, led to forest abandonment and regrowth mainly from the 1956 onwards (Infante-Amate et al. 2014; Marull et al. 2015; Cervera et al. 2016). Inputs coming from outside the local system boundaries, still mainly for cropland uses at that time (industrial fertilizers, tractors), grew rapidly and turned this mixed organic-industrial agriculture more dependent on EI and less based on internal BR. Yet the combination of organic and industrial fertilizers, the coexistence between horses and tractors, as well as the rotation of grains with leguminous crops, also meant that to some extent traditional landscape mosaics were also kept in place in 1956.

Indeed, the distribution of cropland, pastureland and woodland was more balanced in 1956 than in 1860, when almost no pastureland existed. Conversely, pastured woodland had nearly disappeared in 1956, as had *formiguers* and transhumant sheep. The multifunctional uses of woodland as a source of timber, fuel, fertilizing biomass and pasture were significantly reduced to only one or two uses. These functions were in part substituted with a larger pasture area (so that livestock populations could still be maintained from local resources), and partially by the introduction of synthetic fertilizers. However, if we expand the perspective from how the agroecosystem was capable of efficiently sustain itself (which, in 1956 it was still quite capable of doing) and the needs of the local population, we observe early signs of unsustainability. Local renewable sources satisfied fewer needs, diets changed (Padrò et al. 2017) and people used fossil energy in kitchens, households and for transport-related needs.

Finally, in 1999 the whole farm system was structured around a much larger livestock density, totally oriented towards the meat industry. Human food and fuel requirements were no longer linked to the local land-use system, but to global agrifood chains and fossil fuel industries. Meat production in the Vallès area was part and parcel of this global system that interlinked many regional specializations. The local agroecosystem was then traversed by enormous energy and material flows that simply moved across the territory. Feed is imported from other countries, while meat produce is delivered to the rest of Spain and Europe. The break of complex energy loops of biomass reuse flows has had direct consequences in energy performance, as efficiency fell, and also in material terms. Unbalances between funds (huge livestock densities in this case) combined with market dependence (huge feed imports embodied with external energy and land) entails that while imported feed is required to maintain livestock, more meat is produced locally than what the local population needs (despite population increase and changes in diets). Finally, and above all, all these imbalances end up generating huge amounts of pig slurry concentrated in the small territory of Vallès County. The incapacity to use this "potential resource" within the same territory results in considerable water and air pollution. What was once a very scarce and precious resource, manure, has become a dangerous residue because of its high spatial concentration.

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