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Article

Landscape Agroecology. the Dysfunctionalities of Industrial Agriculture and the Loss of the Circular Bioeconomy in the Barcelona Region, 1956-2009

Claudio Cattaneo[1,2,*], Joan Marull[2] and Enric Tello[3]

[1] Department of Environmental Studies, Faculty of Social Studies, Masaryk University, Jostova 10, Brno, Czech Republic claudio.cattaneo@uab.cat
[2] Barcelona Institute of Metropolitan and Regional Studies, Autonomous University of Barcelona, Bellaterra, Spain; joan.marull@uab.cat
[3] Department of Economic History, Institutions, Policy and World Economy, University of Barcelona, Barcelona, Spain; tello@ub.edu
* Correspondence: claudio.cattaneo@uab.cat; Tel.: +34-93-586-8862

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Abstract: The paper analyses how between 1956 and 2009 the agrarian metabolism of the Barcelona Metropolitan Region (BMR) has become less functional, losing circularity in biomass flows and in relationship to its landscape. We do so by adopting a Multi-EROI and flow-fund (MuSIASEM) analyses and its nexus with landscape functional structure. The study of agricultural flows of Final Produce, Biomass Reused and External Inputs is integrated with that of land use, livestock, power capacity and population changes between 1956 (at the beginning of the Green Revolution) and 2009 (fully industrialized agriculture). A multi-scale analysis is conducted at the landscape scale (seven districts within the Barcelona metropolitan region) as well as for the functions deployed, within an agroecosystem, by the mutual interactions between its funds (land-uses, livestock and farming population). A complex nexus between land, livestock, dietary patterns and energy needs is shown; we conclude that from the perspective of the circular bioeconomy the agrarian sector has gone worse hand in hand with the landscape functional structure. Therefore, a novel perspective in landscape agroecology is opened

Keywords: Landscape Agroecology, MuSIASEM, Multi-EROI, Circular bioeconomy, Barcelona Metropolitan Region, industrial agriculture

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1. Introduction

Agrarian industrialization, via the Green Revolution, has allowed unprecedented improvements in land and labour productivity but, in such a production-oriented perspective, its true costs have been overseen [27, 28]. Since the production process, like in an industrial system, is conceived as a linear and highly specialized one –i.e. by increasing inputs to increase output—, the agro-ecological practices [68] of traditional organic agriculture, centered on the multi-functionality of biomass flows and on an equilibrated interdependency —i.e. by means of a mixed farming— of its fund elements (i.e. cropland, pastureland, forestland, livestock, power capacity, farmers) have been left behind.

The increase of animal products in diets [67] has further exacerbated the disruption of the delicate equilibrium between funds, resulting in an increase of livestock densities and feed oriented crops while the increase of highly productive feedlots has modified the landscapes [38, 66]. A new perspective is opened in landscape agroecology [14, 63], one that envisions agroecological landscapes [69]. From a sustainability perspective this is an important issue because the combined effect of agro-industrialization and dietary change –namely, more meat for a cheaper price— has considerable hidden costs in terms of energy efficiency, landscape ecology, bio-cultural heritage, biodiversity, climate change, soil and water quality, and human nutrition and health [69].

The purpose of this work is to demonstrate, when dealing with issues of sustainability and agriculture, the relevance of the landscape agroecology approach: this is an integrated approach that conceives sustainable agriculture not simply as organic or local agriculture but as a set of practices meaningful at landscape scale, that is where all types of ecosystem services play a role. For instance little has to be said about the sustainability of organic agriculture if this depends on inputs that are not

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interwoven with the local agroecosystem, or if it provokes land use changes that destroy habitats and bio-cultural heritages, or if harvest by-products have lost any value [36]. In other words, sustainability in agriculture cannot be conceived without the recognition of the complex socio-metabolic relationships stemming from agroecological practices imprinted in the landscape.

The general hypothesis is that the land-cost of sustainability [27], which is an environmentally extended example of the social costs of business enterprise [70], is not being recognized in current policies and market dynamics. Our specific hypothesis is that sustainability can be assessed by the use of flow/fund models and the related energy and landscape efficiency indicators [20, 41, 57]. In particular, when the modelled agro-industrial practices and land uses break certain flow/fund relationships, multiple losses in ecosystem services, energy and landscape efficiency are observed.

The current state of research in landscape agroecology is set in the outcomes of the Sustainable Farm Systems research project, which has focused on an innovative development of EROI analysis [29, 41, 69, 71] also merging it with MuSIASEM [74], on nutrient cycles [72, 73] and on the original development of Energy-Landscape Integrated Analysis [40-43], which in turn draw from previous work on social metabolism [20, 75, 77] and EROI analysis [76]. As well, these novel methods applied in landscape agroecology can bridge with and contribute to the land sharing/sparing debate [78] which is still a controversial issue [79, 80]

The main aim of this paper is to assess, for the case study of the Barcelona Metropolitan Region, the loss in sustainability that has occurred as a result of agricultural industrialization by highlighting the virtues of a past model that could inspire future developments towards more sustainable agriculture, landscape and diets. In conclusion, we propose multi and inter-functionality of farm practices within their landscape as well as the need for dietary change away from industrial meat production.

The paper is structured in the following way: next section presents the case study, which is the BMR, composed of 7 counties and 164 municipalities for the years 1956 and 2009, the materials and sources used for the analysis and the methods employed. Section 3 presents the results that integrate the Multi-EROI analysis [57, 17, 29] and the MuSIASEM analysis [20] with a specific focus on the nexus between the main agroecosystem funds, the intensity of their flows and the variation between 1956 and 2009. Section 4 discusses the results, in particular how the proportions between the main funds have changed, allowing for an increase in the relative productivity of specific products –meat in particular— but at the cost of a disintegration of the flows connecting these funds, so that a shift has occurred from a circular flow representation towards a "linear" one, resembling an input-output industrial system of a lower agro-ecological quality. It finally presents the results in the light of landscape agroecology. Section 5 concludes.

2. Materials and Methods

2.1 The case study

The Barcelona Metropolitan Region (BMR) is a very densely populated area and the sixth largest urban area in Europe [58, 59]. It is composed of seven counties. Two at the centre, on the coast: Barcelonés -the smallest and most populated— and, to the west, Baix Llobregat with an important agrarian park, together they make most of the Barcelona Metropolitan Area (BMA), which is the most urbanized part of the BMR. At the centre, off the coast is Vallès Occidental, with also a large population; to the north-east are Maresme, on the coast and Vallès Oriental inland; and to the south-west, Garraf, on the coast and Alt Penedés inland.

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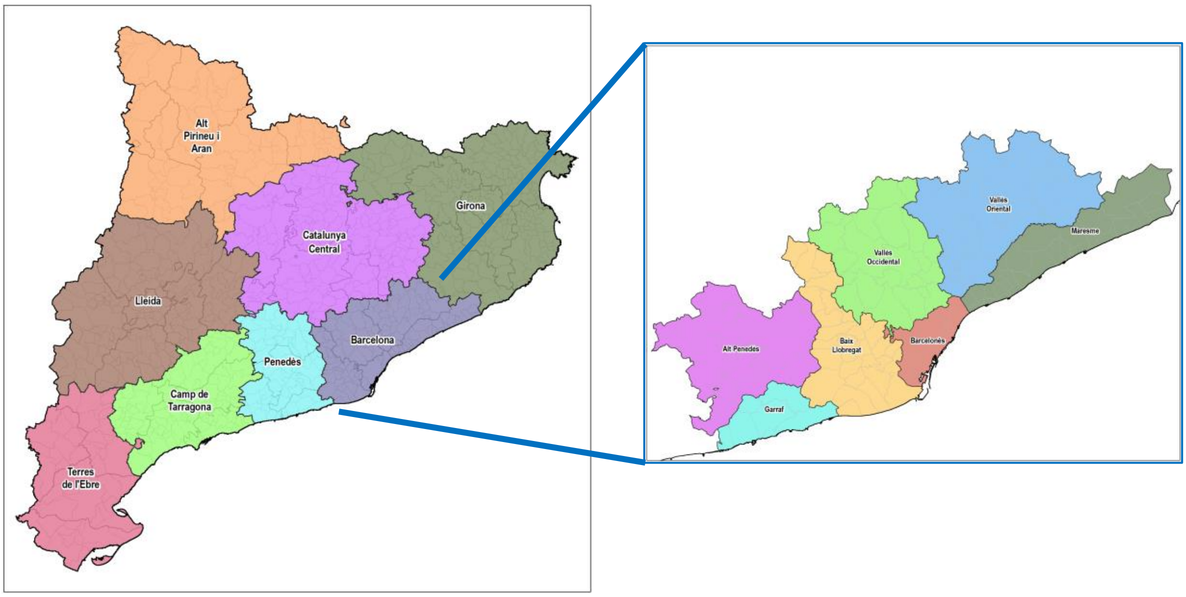

Figure 1: The seven counties of the BMR within the seven regions of Catalonia. Source: our own

Population in the BMR has nearly doubled, reaching 5 million, more than 1,500 hab/km2. Urban area has grown even more, mainly at the cost of agricultural land. Recently there has been a growing public interest towards the implementation of urban and peri-urban agriculture [37], the need for policies oriented to the re-ruralization of the city, the foment of an urban food policy [3], and new territorial planning that considers restoring cropland as much as possible with respect to 1956 levels [23].

2.2 Methods

The analysis is based on a flow-fund representation of the agroecosystem of the BMR for the years 1956 and 2009 across different scales. The funds analyzed are land, in particular woodland, pastureland, cropland (green crops, vineyard and other woody crops), shrub land and built-up land (urban and transport infrastructure); livestock (equids, bovines, sheep and goats, swines, poultry and rabbits); population (total inhabitants and farmers) and machinery power capacity.

The estimation of the land areas in 1956 and 2009 is based on cartographic information available at the municipal level, and then aggregated at the county and the BMR levels. For determining at municipal level livestock heads, farmers population and available machinery we have used for year 2009 online statistical information from the Catalan Statistics Institute (IDESCAT). For 1956 we have used the Spanish Statistical Institute (Instituto Nacional d'Estadistica, INE) [35] for livestock heads; for farmers population we have first determined from INE (1956) the ratios of farmers over total population in urban, intermediate and rural municipalities of Barcelona province and then applied these ratios to 1956 IDESCAT population data; machinery power capacity was available for 1969 for each municipality of the province [12]; based on the Spanish growth levels in the 1955-1962 period [45,46] and knowing Barcelona power capacity for 1962 we have estimated that back in 1956 capacity was 9% of that in 1969. Livestock heads have been transformed into LU500 (units equivalent to 500 kilograms of live weight) by using the same weight coefficients in [38].

Flow estimates (outputs) have been more complex to estimate from statistical sources because of their geographical aggregation at provincial level and their incompleteness related to by-products and unharvested biomass—which are fundamental for our Multi-EROI analysis. As well, extraction from pastureland depends on animal feeding balances at municipal level, in which municipalities with higher livestock densities are expected to extract more from the pastures found within the municipal territories.

In detail, cropland productivity is available from [34, 47] with information for 37 crops grouped in 11 sub-categories: cereals, leguminous, forage, industrial, potatoes, horticulture (they constitute the

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"green crops" category); citrics, fresh fruits, nuts, olives (they constitute the "other wood crops" category) and vineyard. The information refers mainly to the main produce (expressed in tons/hectare) and for 1956 only some by-products: weight of straw and of pruned branches. Using [30] we convert weight into energy and if not already available from statistics the straw/grain, pruning/fruit or any other residue/product ratios. In this way we have determined the main product and by-product for the 11 sub-categories expressed in GJ/ha. From [12] and IDESCAT (2009) we obtain the county-specific area distribution of these 11 sub-categories, we then define county-specific energy flow values and aggregate them for the 3 cropland categories. Given the distribution of green, vineyards and other wood crops per municipality of each county we can define the cropland energy flows at municipal level. Table 1 below show the relationship between cropland typologies and geographical aggregation of the data.

Table 1. Weighting process for cropland energy flows. Flows per hectare in bold; areas in italics.

Source	Provincial Level Idescat	County level - Idescat	Municipal level - GIS	
Categories (detailed and semi-aggregated)	**GJ/ha (11 categories from 37 crop typologies**)	*Area Distribution (11 categories in %)*		
Categories (aggregated)		**Aggregation of county level energy flows GJ/ha (3 categories)**	*Area Distribution (3 categories in %)*	Spatially explicit energy flows
			Municipality-specific flows (3 categories)	

Source: Our own.

We then define which parts of the product and by-product constitute final produce and which constitute biomass reused or unharvested biomass. From [46, 47] we obtain the amount of main produce destined to seed and feed and from [38] we determine the amount of re-ploughed biomass and cereal husks as a percentage of the main product, so that we are able to define biomass reused from cropland back to cropland (seeds and reploughed biomass) and to livestock (straw, husks and feed). As well, we define the amount of unharvested biomass: weeds, from [30] and herbivory from the method employed in [50].

For woodland productivity we obtain information from [34] –data aggregated at provincial scale—, and from [10] with data at county level. Volumes are then transformed into weight and then into GJ. Woodland Net Primary Productivity (NPP) is assumed equal to NPP0 and has been obtained from [21] where the values of Italy have been used as a reference.

To compensate for seasonal variability, the productivity volumes of woodland and cropland (37 typologies) have been adjusted to the average between 1954 and 1958 (based on Spanish aggregated data) and between 2007 and 2011 (based on Barcelona province data).

Pastureland extraction for 1956 has been determined based on each municipality's animal feeding needs once supply from more easily available sources (feed-oriented crops, cropland by-products and domestic residues) has been used up. Since in 1956 it was common that animals were grazing in sparse woodlands (the Spanish *dehesa*) we have assumed that pasture from woodland is also available. For 2009 it is assumed that animals use pasture minimally so that each municipality has excess pasture. The productivity values have been obtained from the method of [38].

We assume scrubland is unharvested land with same NPP as in [38].

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Livestock flows are the energy value of slaughtered animals by assuming the farmgate hypothesis: the output flow considered as final produce is the energy content of their weight, and not only the edible part. Slaughter rates have been derived from [38]. For 2009 there are Spanish aggregated data on trade of live animals [1] which have also been estimated. IDESCAT provides milk egg and wool productivities. All data expressed in weight or litres have been transformed into energy using the coefficients in [30].

Animal feeding has been calculated as in [38]. For 1956 we assume that it was closely integrated with products and by-products of local cropland, pastures and domestic residues and, only in case of a supply deficit there would be imports from eventual surplus in nearby municipalities and counties.

The balance has been determined based on the capacity each animal typology has to metabolize different sources of feed, and on some assumptions of livestock breeding back in 1956—i.e. ruminants better metabolize straw than monogastric which, in turn, are more likely to live in household backyards, while ruminants would more likely be fed on forage and pastures. The table below shows per each animal typology the feeding sources in 1956

Table 2: feeding sources modelled per each animal typology[1]

	Straw (cereals leguminous)	**Grains (cereals leguminous)**	**Forage**	**Pastures (meadow woodland)**	**Acorns (woodland)**	**Potatoes, garden by-products**	**Domestic residues**
Equids	Y	Y	Y	Y	X	X	X
Bovins	Y	Y	Y	Y	X	X	X
Sheep, goats	Y	Y	Y	Y	X	X	X
Swines	X	X	X	X	Y	Y	Y
Poultry rabbits	X	Y	X	X	X	Y	Y

[1]Y = Yes, X = No

Source: Our own.

A back-and-forth method has been used to determine the biomass flows from cropland to livestock: first, straw for stall bedding has been defined; then, if excess straw was available, it would be counted as feed for ruminants and distributed proportionally to the feeding demand of each ruminant typology; if not, straw would be imported and local ruminants would not be fed on local straw. Feed-oriented crops (grains and forage) have then be balanced between supply and demand, by being allocated in proportion to each typology's feeding demand and, in case of excess supply, this would count as Cropland Final Produce; if local supply is used up, only then local pastures would be used and its access distributed proportionally. In some cases once the feeding needs were satisfied, there was still pasture productivity in excess of demand, so that the NPP in excess would count as unharvested biomass. In other cases, there was not enough feed or pasture for local demand. Farmers from these municipalities would import straw forage and grains from nearby ones or from other counties. The same process has been done for monogastric animals, where first grains (to chicken and rabbits) then potato and garden residues, then domestic residues and finally acorns in woodland (to swines) were allocated. If demand was still not met in the process, then feed would be imported from nearby municipalities or counties.

For 2009 we assume a more simple hypothesis in which animal feeding is not primarily related to local cropland and pastures but to feeding tables that combine a mix of feed that is cultivated locally and other that is to be imported (such as soybean meals). The method is that proposed in [38].

Note that what can be considered as final produce at municipal level –i.e. feed oriented crops in excess to local feeding demand at county level it could be considered as biomass reused from cropland to livestock. In turn, municipalities that import feed from others in the same county would have these inputs counted as external input while at the upper scale it would count as biomass reused.

According to Tello et al.'s method [57] other input flows refer to: Farming Community Inputs (the exosomatic energy of farmer's work and, for 1956, humanure) and Agroecosystem Societal Inputs (ASI) (imported seeds, with data available from national statistics and from [38] and domestic residues of all households in rural municipalities and of 30% of them in county capitals and urban municipalities). Moreover, for both 1956 and 2009 there are ASI of non-renewable nature: machinery, synthetic fertilizers, biocides and electricity for pumping irrigation water and, for 2009 only, also electricity for running feedlots. [2]. Data on fertilizers and biocides consumption is available only at national or Catalan level for time points 1956 and 2009 respectively. Electricity consumption is based on an estimation of energy use per hectare of irrigated land or per animal head [2] for the 1956 time point, and [38] for the 2009 time point.

Biomass reuses notably flow from farmland to livestock. However, there are also flows from livestock back to cropland (known as Livestock Services) which, for the sake of the EROI energy balance constitute double accounting and are not accounted for but that, for the MuSIASEM approach are relevant (i.e. manure is a substitute of synthetic fertilizers) and also for the study of the nexuses between different funds (i.e. work animals vs. machinery) as well as for studying the landscape imprint of agriculture energy flows [41]. Manure flows and draught power have been estimated following [38].

Finally, waste flows have been considered. Following [49] these are considered as resources out of place, namely they are: feedlot slurry in excess of cropland Nitrogen carrying capacity; by-products of pruning burnt on field and burnt biomass from forest and shrub land wildfires due to lack of management. While the first two have been estimated following the method in [38], the latter has been estimated for year 2009 based on forest fire Catalan statistics and using the same assumptions made on the proportion of biomass burnt in such fires. For year 1956 it is assumed that pruned branches were burnt for cooking purposes and forest fires where not present as woodland was, in general, pastured and still exploited.

The analysis is then carried out calculating a set of different EROI [57, 17 and 28] and other flow/fund and fund/fund indicators based on the MuSIASEM approach [20]. In particular, we are exploring the nexus between farmland and livestock functions as in the figure below which shows the nature of energy flows inside and outside the agroecosystem (EI and FP), and between its compartments (BR from cropland, pastures and forests to livestock and BR from livestock back to cropland). Figure 1 shows how energy and biomass flows go through and across different elements of an agro-ecosystem. Of particular interest are flows of reused biomass, from farmland (cropland, pastures and forests) to livestock and livestock services back to cropland. As well, external inputs and final products enter and exit the agroecosystem's farmland and livestock compartments.

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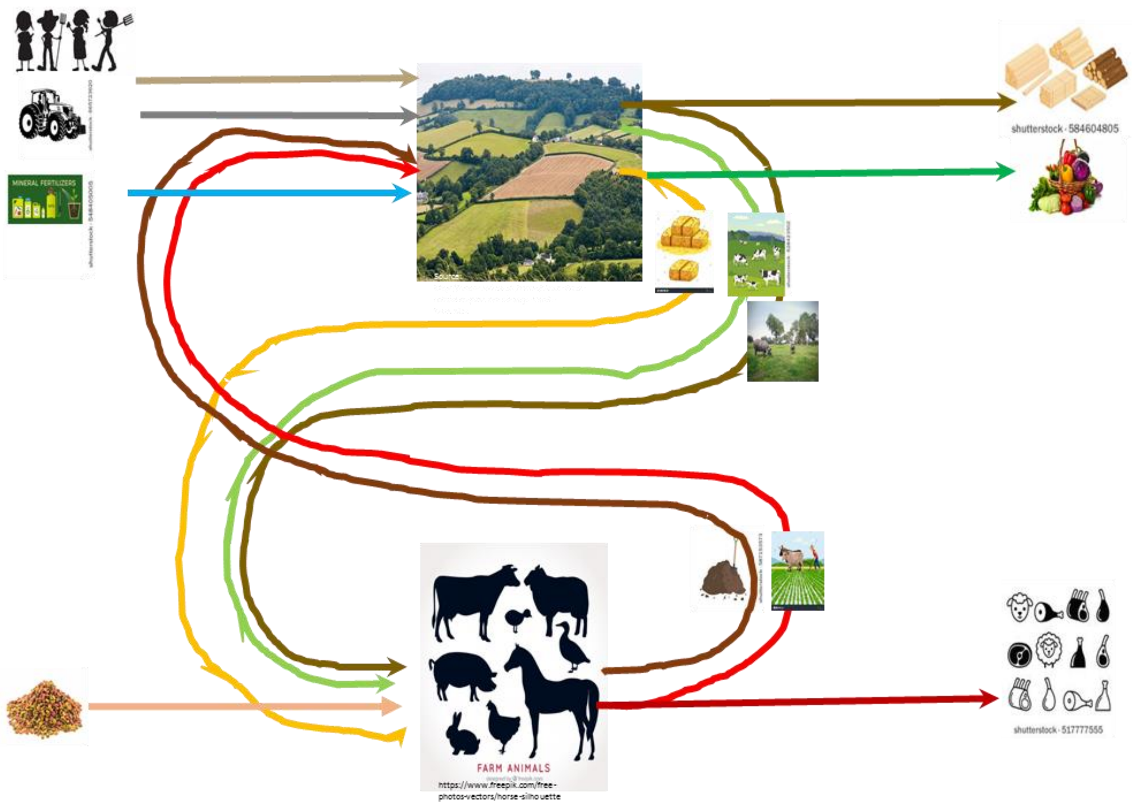

Figure 2: representation of an agro ecosystem's multi-functionality. Source: Our own.

2.2.1 Landscape agroecology metrics

We use two landscape metrics. The Shannon index (H) applied to the land-cover structure is used as an indicator of landscape's heterogeneity, and as a proxy for habitat differentiation that hosts biodiversity [62]. From a landscape agroecology perspective, we adopt a variation of it –the geographical distribution index— to create a proxy also for agricultural multi-functionality:

$$H = -\sum p_i \log_k p_i \quad (1)$$

in which k are the different land covers of a territorial unit of analysis (i.e. the Alt Penedés county) and p is the size of land cover i expressed in relation to the unit of analysis. Its landscape agroecology variation applies the formula to show how a fund (i.e. woodland land cover, or poultry animal typology, or population) is distributed across k regions, where p is the size of the fund in region i with respect to the total sum of that fund over the k regions.

The index ranges between 0, representing maximum homogeneity, which is one land cover in the unit of analysis or, in its variation, the fund entirely concentrated in one region; and 1, representing maximum heterogeneity through equidistribution of land covers in the unit of analysis or, in its variation, equidistribution of the fund in each region of the BMR.

We also adopt the Ecological Connectivity Index (ECI) [40], related to land-cover functionality, which measures in a [0,1] range the capacity for connecting flows of biomass and information across a territorial unit of analysis, which is fundamental for supporting biodiversity and related ecosystem services.

3. Results

For simplicity of presentation of results, the analysis is done at the county and BMR level. Detailed results for each municipality are included in Annex 1. First the evolution of the main funds is presented, then the EROIs indicators and finally their flow/fund representations.

3.1. Cropland loss, livestock growth, mechanization and urbanization

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Across the BMR cropland area has gone down from 40% to 18% of the territory, losing it to urban area which is up from 5% to 23%, and to woodland that has grown from 37% to 42%. Table 3 shows the evolution in the area of urban and farmland categories in each county and the landscape agroecology indicators. The Shannon index accounts for six land covers: green crops, wood crops, vineyards, meadows, shrub land and woodland; between 1956 and 2009 their heterogeneity has gone down in all counties. The variation in the Ecological Connectivity Index shows that it has always gone down too. Finally, the geographical distribution of each land use is presented in the bottom line. The index, which applies the Shannon Index formula for 1956 and 2009, shows how the surface of each land use is distributed across counties and indicates that in 2009 meadows and cropland –and all its sub-categories- were less evenly distributed—the Index falls from 0.96 to 0.90 (meadows) and from 0.91 to 0.78 (cropland). In particular, the geographical localization of vineyards is increasingly skewed towards Alt Penedés: this is the crop category which has decreased the least in surface, but has reached the most uneven distribution. On the other hand, woodland and urban areas are more evenly distributed in the Region than they were in 1956. As well, population has increased the most outside Barcelonès County (Table 5).

Table 3. Land use categories (and cropland sub-categories): area in km2; Shannon Index of non-sealed land uses; average loss in Ecological Connectivity Index; Geographical distribution index of land uses across counties

		Land uses, km2										
		Urban	Cropland	*Green crops*	*Wood crops*	*Vineyards*	Meadows	Shrubland	Woodland	Total	Shannon (6uses)	Average loss in ECI
Alt Penedés	1956	12	336	*148*	*25*	*163*	7	123	111	593	0.85	-20%
	2009	50	250	*42*	*17*	*191*	17	78	190	593	0.78	
Baix llobregat	1956	21	205	*101*	*76*	*27*	14	104	128	486	0.87	-42%
	2009	147	60	*34*	*22*	*4*	20	87	148	486	0.65	
Barcelonés	1956	58	37	*35*	*1*	*1*	8	15	15	142	0.59	-37%
	2009	112	1	*1*	*0*	*0*	1	14	16	145	0.30	
Garraf	1956	6	66	*27*	*19*	*19*	2	70	37	184	0.84	-31%
	2009	39	24	*10*	*4*	*10*	5	57	55	185	0.67	
Maresme	1956	15	146	*110*	*15*	*20*	12	41	179	397	0.74	-47%
	2009	92	44	*37*	*4*	*3*	13	34	207	398	0.54	
V. Occidental	1956	29	208	*154*	*22*	*32*	12	66	256	583	0.74	-42%
	2009	165	65	*57*	*7*	*1*	18	68	249	583	0.56	
V. Oriental	1956	20	268	*233*	*26*	*10*	10	72	475	851	0.61	-33%
	2009	140	125	*114*	*8*	*2*	23	60	492	851	0.52	
RMB	**1956**	**161**	**1,266**	***808***	***185***	***272***	**65**	**492**	**1,201**	**3,236**	**0.81**	**-36%**
	2009	**746**	**567**	***294***	***62***	***211***	**98**	**397**	**1,357**	**3,240**	**0.67**	
Geographical distribution	**1956**	**0.89**	**0.91**	**0.91**	**0.84**	**0.67**	**0.96**	**0.94**	**0.82**	**0.93**		
	2009	**0.95**	**0.78**	**0.82**	**0.82**	**0.23**	**0.90**	**0.95**	**0.86**			

Livestock units have increased by 40% but not in a uniform way. The most evident effect has been the near to disappearance of work animals and a general substitution of monogastric species –swines in particular- for ruminants, the latter go down from 92% of total LU500 to 39%. The other important effect is a shift in regional specialization from Barcelonès to Vallés Oriental. In 1956 the Barcelonès concentrated 32% of the RMB's LU500, mainly because of milk-producing vaqueries (because of the quick perishability of milk they had to be close to the place of consumption [51, 52]. In 2009 Vallés Oriental concentrated even more LU500 (62%). As a consequence the general livestock distribution index has decreased from 0.89 to 0.60 and that of most animal typologies has also decreased from around 0.80 – 0.90 to around 0.50 – 0.60 (Table 4).

Table 4. Livestock composition, geographical and typology distribution indexes

LU500	**As a % of total LU500**

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		Cattle	Sheep &goats	Equids	Swines	Poultry &rabbits	Total	Cattle	Sheep &goats	Equids	Swines	Poultry &rabbits
Alt Penedés	1956	482	712	2,059	154	357	3,765	13%	19%	55%	4%	9%
	2009	2,132	650	159	2,408	4,337	9,686	22%	7%	2%	25%	45%
Baix llobregat	1956	1,591	442	2,063	227	232	4,554	35%	10%	45%	5%	5%
	2009	489	458	169	286	35	1,436	34%	32%	12%	20%	2%
Barcelonés	1956	7,252	737	6,525	963	120	5,597	46%	5%	42%	6%	1%
	2009	0	3	4	0	0	7	0%	43%	55%	0%	1%
Garraf	1956	303	269	455	50	65	1,141	27%	24%	40%	4%	6%
	2009	120	226	113	2	42	503	24%	45%	22%	0%	8%
Maresme	1956	4,029	197	1,971	141	235	6,573	61%	3%	30%	2%	4%
	2009	2,039	321	220	2,737	1,077	6,394	32%	5%	3%	43%	17%
Valles. Occidental	1956	2,645	416	2,107	210	282	5,659	47%	7%	37%	4%	5%
	2009	2,009	608	390	4,225	594	7,825	26%	8%	5%	54%	8%
Valles. Oriental	1956	7,087	531	2,847	340	392	11,196	63%	5%	25%	3%	3%
	2009	14,142	2,102	317	23,910	1,412	41,883	34%	5%	1%	57%	3%
RMB	1956	23,389	3,303	18,027	2,084	1,682	48,486	48%	7%	37%	4%	3%
	2009	20,931	4,368	1,370	33,567	7,497	67,733	31%	6%	2%	50%	11%
Geo. distrib Index	1956	0.82	0.96	0.89	0.82	0.94	0.89					
	2009	0.55	0.77	0.88	0.48	0.60	0.60					

Population has also increased, but not as much as urban area so that the allowance of urban and cropland area per capita has changed dramatically: the result is growth in the urban area per capita (+140%) and a sharp decrease in the cropland area per capita (-77%); the urban/cropland area ratio has grown from 0.13 to 1.31. (Table 5)

Farmers have decreased even more than cropland area (-88%) so that each one now cultivates on average almost 8 ha, up from just above 2 ha in 1956. Even more remarkable is the growth in LU500 per farmer: from 0.8 to 9.3, mainly because of large feedlots in the Vallés area experiencing peaks of 20 to 40 LU500/farmer. Power capacity per farmer went up from 0.6 hp –70% of which was animal power- to 90 hp in 2009 peaking at 150 to 260 in both Vallés. Mechanization was at its beginning in 1956 and machinery growth rates were in double digits and have maintained a similar pace throughout the second half of the XXth century. In summary, endowments per farmer have increased by a factor 4 (cropland), by a factor 10 (livestock) and by a factor 150 (power capacity).

An important indicator is the evolution of livestock density measured in LU500/ ha cropland, that has grown from 0.4 to 1.2, reaching 3.36 in Vallés Oriental. Instead, cropland per capita has decreased sharply. Table 5 shows the main relationships across funds for each county.

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		Population and fund/fund relationships				Farmers and fund/fund relationships					Cropland and fund/fund relationships				Population
		population	pop density	m2 cropland /cap	m2 urban /cap	farmers	ha cropland /farmer	LU500/ farmer	hp(m)/ farmer	hp(a)/ farmer	cropland, ha	LU500/ ha	hp(m)/ha	hp(a)/ha	(% of RMB) and distribution
Alt Penedés	1956	47,281	80	7,110	246	9,095	3.70	0.41	0.26	0.35	33,617	0.11	0.07	0.09	2%
	2009	104,353	176	2,391	479	2,616	9.54	3.70	90.95	0.09	24,956	0.39	9.54	0.01	2%
Baix llobregat	1956	174,155	358	1,176	122	8,609	2.38	0.53	0.25	0.37	20,480	0.22	0.10	0.15	7%
	2009	793,655	1,634	76	185	918	6.56	1.56	63.97	0.28	6,021	0.24	9.75	0.04	16%
Barcelonés	1956	1,821,324	12,821	20	32	12,170	0.30	1.28	0.03	0.82	3,674	4.25	0.10	2.72	71%
	2009	2,251,600	15,475	0	50	54	1.55	0.12	41.90	0.10	84	0.08	27.12	0.07	45%
Garraf	1956	39,869	217	1,651	147	1,889	3.49	0.60	0.21	0.37	6,583	0.17	0.06	0.11	2%
	2009	143,066	774	165	273	209	11.28	2.41	102.59	0.81	2,360	0.21	9.09	0.07	3%
Maresme	1956	125,660	316	1,160	118	9,238	1.58	0.71	0.14	0.33	14,582	0.45	0.09	0.21	5%
	2009	426,565	1,072	103	217	2,044	2.16	3.13	38.60	0.16	4,407	1.45	17.91	0.07	9%
V. Occidental	1956	268,386	461	776	109	8,995	2.32	0.63	0.17	0.36	20,832	0.27	0.08	0.15	10%
	2009	878,893	1,508	74	188	372	17.38	21.05	262.03	1.57	6,462	1.21	15.08	0.09	18%
V. Oriental	1956	90,058	106	2,979	226	12,294	2.18	0.91	0.24	0.35	26,829	0.42	0.11	0.16	4%
	2009	394,061	463	316	355	1,095	11.37	38.25	148.76	0.43	12,451	3.36	13.08	0.04	8%
RMB	**1956**	**2,566,733**	**793**	**493**	**63**	**62,289**	**2.03**	**0.78**	**0.18**	**0.44**	**126,597**	**0.38**	**0.09**	**0.22**	**0.55**
	2009	**4,992,193**	**1,541**	**114**	**149**	**7,309**	**7.76**	**9.27**	**90.25**	**0.28**	**56,741**	**1.19**	**11.63**	**0.04**	**0.80**

Table 5. Fund/fund relationships (population and farmers; livestock, area and power capacities). Source: Our own from the data sources given in the text.

3.2 Increased energy inefficiency

Following [17 and 22] we present eight EROI indicators.

With the exception of Barcelonès, where Livestock has nearly disappeared, FEROI has gone down in each county from around 0.8 to around 0.2, with the highest value in Baix Llobregat (0.36). IFEROI has in general gone up (at RMB level from 0.9 to 1.3)—implying less biomass recirculation from land to cropland and to livestock. EFEROI has decreased sharply, overall from 1.2 to 0.2. In most counties it used to be above 2 and even up to 3.6 in 1956 while in 2009 it was only between 0.14 and 0.42, meaning that the large increase in inputs (mainly machinery and imported feed) have outnumbered higher farm or livestock final productivity.

NPPEROI, which relates NPP with the sum of total inputs consumed (TIC) and unharvested biomass, has gone down: while NPP has maintained, the unharvested part of NPP has increased –mainly due to forest transition, and TIC have grown exponentially in every county except Barcelonès. The Agroecological EROI, which relates FP to the sum of unharvested biomass and TIC, has approximately halved in all counties. Biodiversity EROI, which relates unharvested biomass to the sum of TIC and unharvested biomass, and which could count as a proxy of biodiversity, has gone down slightly because except in Barcelonès TIC have gone dramatically up.

Land EROI has gone down from 3.27 to 0.2, with the highest value in Baix Llobregat (0.39) –it counts on 65% of irrigated cropland against an average of 27%— and in Vallès Oriental (0.28) where forest extraction per hectare is highest. Feedlots, modern feeding apt for monogastric animals and elimination of work animals are a very linear-efficient way to fatten livestock while in the past ruminants, open-air grazing and work animals prevailed. As a result, Livestock EROI is the only indicator that has increased, from 0.05 to 0.1 (dominated by Maresme, Alt Penedès and Vallès Occidental where monogastric constitute more than 60% of LU500). From an input-output perspective livestock productivity is much lower than land productivity.

In summary, even if Land and Livestock EROI values have converged, the former is still much higher than the latter. This implies that the growth of livestock final produce over final produce (LFP/FP), up from 8% to 19%, has led to less energy efficient agriculture (see the variation in LFP/FP plotted against the variation in FEROI of Figure 3): when LFP/FP has gone down to nearly zero, as in the Barcelonès, FEROI has increased by nearly 40%; where LFP/FP has boomed, as in Alt Penedès (up from 2% to 21%), FEROI has collapsed by 80%.

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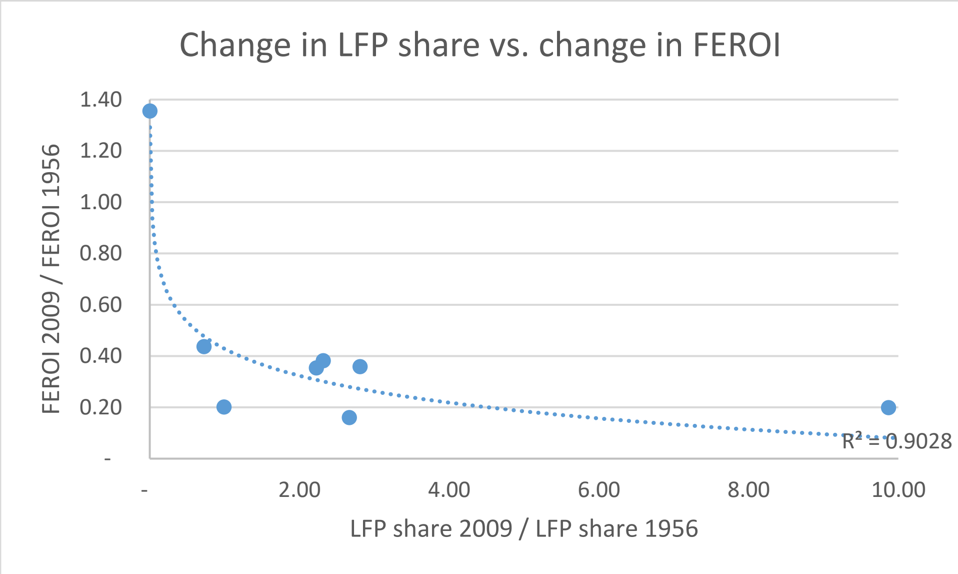

Figure 3. Change in LFP share vs. change in FEROI. Source: Our own.

3.3 Spatially explicit Flow/fund relationships: nexus and landscape ecology

The table below represents the overall per hectare flows of FP, BR and EI in which, at a glance, is possible to see how lower biomass flows are substituted for higher flows in external inputs.

Table 6. Change in FP/ha, BR/ha, EI/ha, in multi-EROI values and in share of LFP. Source: Our own.

		FP/ha	BR/ha	EI/ha	FEROI	IFEROI	EFEROI	NPP EROI	Agroec EROI	Biodiv EROI	Land EROI	Livestock EROI	LFP share
	1956	13,87	10,80	4,93	0,88	1,28	2,81	1,19	0,30	0,66	3,30	0,03	0,02
Alt Penedés	2009	17,27	6,35	92,42	0,17	2,72	0,19	0,61	0,12	0,33	0,16	0,15	0,21
	1956	18,14	13,18	8,69	0,83	1,38	2,09	1,14	0,29	0,64	3,93	0,04	0,04
Baix llobregat	2009	14,69	5,25	35,38	0,36	2,80	0,42	0,84	0,14	0,61	0,39	0,07	0,03
	1956	27,89	27,96	261,47	0,10	1,00	0,11	0,21	0,09	0,08	1,83	0,05	0,52
Barcelonés	2009	1,78	0,67	12,95	0,13	2,66	0,14	0,90	0,02	0,83	0,14	0,00	0,00
	1956	10,87	8,50	5,09	0,80	1,28	2,13	1,12	0,23	0,71	3,60	0,04	0,04
Garraf	2009	5,72	4,20	31,43	0,16	1,36	0,18	0,80	0,06	0,61	0,19	0,03	0,04
	1956	16,78	20,56	9,44	0,56	0,82	1,78	1,07	0,22	0,61	3,63	0,06	0,09
Maresme	2009	13,42	13,57	54,44	0,20	0,99	0,25	0,72	0,09	0,55	0,20	0,11	0,21
	1956	17,25	14,98	5,24	0,85	1,15	3,30	1,16	0,24	0,72	4,02	0,05	0,05
V. Occidental	2009	8,06	10,95	48,46	0,14	0,74	0,17	0,71	0,06	0,57	0,15	0,05	0,13
	1956	16,78	18,06	4,65	0,74	0,93	3,61	1,13	0,21	0,72	3,74	0,07	0,08
V. Oriental	2009	20,28	12,50	64,24	0,26	1,62	0,32	0,69	0,13	0,51	0,28	0,10	0,22
	1956	14,93	16,91	12,45	0,51	0,88	1,20	1,02	0,20	0,61	3,27	0,05	0,08
RMB	2009	13,74	10,63	60,32	0,19	1,29	0,23	0,69	0,10	0,49	0,20	0,10	0,19

This is a clear result of agricultural industrialization in cropping and in livestock breeding in which cheaper industrial inputs and feed substitute for local biomass flows. However, there is a more nuanced picture when these relationships are calculated for the different land uses and with respect to LU500 livestock densities.

Productivity per hectare of major crops has increased in terms of main produce. Primary data show that the main product of cereal crops (which constituted 50% and 81% of green crop area in 1956 and 2009 respectively) has increased from 13.9 to 49.6 GJ/ha. Grapes productivity in vineyards (constituting 21% to 37% of all cropland) has also increased from 11.8 to 27.6 GJ/ha. However, in terms of biomass recirculation and final productivity there is a lower capacity to take advantage of products from wood crops, meadows and woodland products, as well as of by-products from any land use typology. For instance in 1956 vineyards, wood crops and woodland were also used for pasture; meadows were exploited at a higher capacity; pruned branches were used for domestic fuel needs; straw was fed to work animals.

The result is a lower per hectare productivity in certain land uses: wood crops final productivity decreased from 45 to 19 GJ/ha; woodland final productivity decreased from 17 to 12 GJ/ha, if BR is also accounted, that is if we consider the pasture in forests that was modelled only for 1956, it went down

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from 24 to 12 GJ/ha; an average of 41% of meadows productivity was pastured versus only 5% in 2009; wood crops and vineyard were offering also just below 1GJ/ha for animals (by grazing or by eating leaves of pruned branches) which was not done anymore in 2009: the amount of BR for livestock has therefore been reduced in almost all land covers but it has paradoxically increased in green crops, because of the increase in feed-oriented cropland area. The table below presents biomass flows per hectare of different farm use categories and per LU500.

Table 7. Biomass and energy flows across land uses and livestock; GJ/ha and GJ/LU500. Source: Our own.

		FP, GJ/ha (GJ/LU500)					
		Green crops	Wood crops	Vineyards	Forest	(Animal)	Total
Alt Penedés	1956	17,83	43,15	13,77	16,87	4,47	13,87
	2009	12,93	16,66	27,56	6,52	19,78	17,27
Baix llobregat	1956	17,92	46,46	13,77	16,87	6,51	18,14
	2009	93,14	20,68	27,56	5,15	8,50	14,69
Barceloné s	1956	20,00	41,26	13,77	16,87	7,02	27,89
	2009	67,70	22,68	27,56	0,31	1,45	1,78
Garraf	1956	13,61	29,81	13,77	16,87	6,28	10,87
	2009	38,32	16,14	27,56	1,05	5,93	5,72
Maresme	1956	15,84	45,25	13,77	16,87	9,12	16,78
	2009	17,33	36,37	27,56	11,03	13,18	13,42
V. Occidental	1956	19,94	48,31	13,77	16,87	7,76	17,25
	2009	14,21	22,91	27,56	7,35	5,16	8,06
V. Oriental	1956	14,10	52,11	13,77	16,87	9,48	16,78
	2009	12,21	11,91	27,56	19,48	7,30	20,28
RMB	**1956**	11,19	45,17	13,77	16,87	7,70	14,93
	2009	13,92	19,44	27,56	11,62	9,41	13,74

		BR, GJ/ha (GJ/LU500)								
		Green crops	Wood crops	Vineyards	Meadows	Forest	From land to livestock	From livestock to cropland	(From land to livestock)	(From livestock to cropland)
Alt Penedés	1956	36,38	0,63	0,83	6,91	4,61	10,20	13,27	156,35	118,49
	2009	80,43	-	-	1,42	-	5,57	23,62	30,75	60,86
Baix llobregat	1956	43,57	0,22	0,43	28,52	8,00	12,65	21,92	125,30	98,56
	2009	47,73	-	-	1,20	-	3,62	8,92	79,71	37,40
Barceloné s	1956	41,19	0,17	0,21	42,05	21,41	27,05	205,49	13,09	48,40
	2009	29,09	-	-	0,63	-	0,44	5,56	207,02	70,07
Garraf	1956	44,76	0,19	0,56	11,66	5,67	8,11	17,83	124,70	102,81
	2009	59,36	-	-	4,42	-	3,49	12,38	97,21	58,03
Maresme	1956	45,07	0,03	0,26	20,59	14,11	19,87	35,93	114,15	79,70
	2009	107,85	-	-	2,50	-	11,90	64,46	55,43	44,44
V. Occidental	1956	43,05	0,74	1,32	11,55	4,97	14,07	26,67	134,75	98,18
	2009	76,33	-	-	2,81	-	9,58	44,65	48,90	36,88
V. Oriental	1956	53,64	0,68	1,58	2,31	4,99	17,00	37,21	125,29	89,16
	2009	75,99	-	-	2,69	-	10,96	122,11	18,32	36,30
RMB	**1956**	**50,85**	**0,38**	**0,81**	**18,82**	**6,86**	**16,13**	**30,37**	**100,63**	**79,30**
	2009	**86,59**	**-**	**-**	**2,22**	**-**	**9,33**	**48,75**	**33,31**	**40,83**

		EI, GJ/ha (GJ/LU500)					
		Green crops	Wood crops	Vineyards	Forest	(Animal)	Total EI per farmland
Alt Penedés	1956	8,20	9,44	2,54	1,51	21,70	4,94
	2009	168,46	87,41	150,36	11,18	104,86	92,54
Baix llobregat	1956	8,24	9,43	2,54	1,32	47,20	8,74
	2009	207,19	82,23	117,78	6,86	50,93	35,21
Barceloné s	1956	11,55	15,54	4,80	4,04	123,47	261,51
	2009	455,67	295,07	395,19	1,43	177,87	12,77
Garraf	1956	7,58	7,63	2,27	1,17	39,80	5,10
	2009	179,19	85,95	153,33	1,84	129,53	31,28
Maresme	1956	8,20	9,33	2,47	1,34	34,17	9,49
	2009	195,57	155,15	131,71	16,50	63,98	53,00
V. Occidental	1956	7,87	8,62	2,25	1,01	19,71	5,26
	2009	192,52	135,56	177,38	14,95	45,28	48,24
V. Oriental	1956	7,64	9,15	2,29	1,12	11,47	4,67
	2009	102,40	43,71	95,55	20,83	52,53	63,58
RMB	**1956**	**7,70**	**9,54**	**2,56**	**1,44**	**56,36**	**12,48**
	2009	**151,04**	**79,58**	**126,57**	**17,36**	**60,81**	**58,22**

Growth in green crops productivity has often resulted in slight increases in FP and large increases in BR. This is because of an increasing amount of green crops dedicated to feed (up from 31% to 72%; or from 19% to 56% with respect to total cropland area). FP/ha in green crops has increased the most in Baix Llobregat, Barcelonès and Garraf which are the counties where livestock population has decreased the most. Even if an increasing part of green crops is destined as BR to livestock, the near to abandonment of animal grazing and pasturing in wood crops, vineyards, meadows and forests results in an overall loss of BR from land to livestock. In turn, this implies more feed imports from beyond the BMR boundaries [66].

4. Discussion

4.1. Landscape agroecology: bridging MuSIASEM with ELIA.

Our research is part of an energy-landscape integrated approach (ELIA) [41, 42] in which we explicit biomass and energy flows across different land uses. ELIA is a novel application of the flow-fund analysis [65]. Moreover, multi-functionality assumes a prominent role in landscape agro-ecology to the point where we can refer to inter-functionality: in the common understanding of multi-functionality one land use can serve multiple purposes (i.e. food, fuel, feed); however, agro-ecological practices require interdependent relationships between farmers, livestock, land-uses and productive capacity. That is, funds become interdependent and requires flows in order to be maintained. By combining the flow-fund approach of ELIA, MuSIASEM and Multi-EROI we are able to represent these dynamics and, hence, offer a more articulated perspective in landscape agroecology

Landscape Agroecology is not a new term [64, 14], it focusses on multifunctional relationships in landscapes [32] and also on interdisciplinary, multi-scale analysis [13]. However, the first novelty of our ELIA-based approach is the introduction of the flow-fund dimension in agroecosystems [29, 57] as a fundamental element for explaining landscape dynamics through energy flows. Secondly, it conceives multi-scalarity not only in its geographical dimension –i.e. how counties have specialized within the BMR— but also as a multi-functional dimension—i.e. the roles of, and the nexus between, land typologies and animals typologies within an agroecosystem. Finally, it is linked to the notion of agrarian multi-functionality which, differently from [61]'s understanding of agricultural multi-functionality as a provider of outputs (ecosystem services to society), it relates to the metabolic perspective on an agroecosystem (level n of analysis) and the functions performed by its internal components (level n-1

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and n-2 of analysis) whose flows allow for both the maintenance of an agroecosystem's fund elements (internal loops) and provide services to society (final flows). We refer to this as inter-functionality because of the complex hub of flow/fund relationship and correspondent flows.

In this way ELIA-based landscape agroecology is also a novel application of MuSIASEM [19,20]: for its flow-fund analytical approach, for the multi-functionality between fund elements at multiple scales, and for the integration of landscape ecology, agrarian studies and social metabolism. Moreover, given the presence in agroecosystems (level n) of a complex and inter-related set of different funds (level n-1) we apply the nexus analysis within MuSIASEM in which we consider the flows associated to the land and livestock functions: the relationships are expressed in energy per hectare and energy per LU500. Finally, given the focus of our analysis on the linearity vs. circularity of flows, we indicate their direction as incoming, outgoing or recirculating across land uses and livestock. In summary, the multi-scale spatial explicitation of energy flows, and the nexus across different agroecosystem funds, are the fundamental bricks of landscape agroecology.

4.2. Agricultural inter-functionality and landscape functional structure disintegrated by industrialization, urbanization and geographical specialization

Industrialization of farming activities is visible in the fall of EROIs, primarily because of the losses in multi-functionality of agrarian flows and in inter-functionality across funds. However, for the specific case of livestock breeding industrialization has implied an improvement in the Livestock EROI: but in this case the costs are visible on the landscape.

Feedlots' economic linear-efficiency –i.e.increased livestock EROI and final meat or eggs productivity is possible only through grain-based diets, stabling and growth in the proportion of monogastric animals (as well as by the growth in the size of feedlots). This process is in antithesis with agro-ecological and landscape efficiency, even more so when livestock densities to cropland have changed this delicate equilibrium, and when machinery substitutes for work animals which in turn explains the lower Land EROI. As a consequence of substituting feedlots for open-air grazing, combined with another land use inefficiency such as the substitution of fossil fuel burning for wooden biomass, the result is a combined lower agroecosystem and landscape efficiency from a circular bioeconomy standpoint. In particular, an apparent win-win situation constituted by a higher availability of animal products and fuel for a cheaper market price is only the tip of an iceberg whose underneath hides a lose-lose-lose-lose-lose-lose-lose (lose7) reality with negative landscape agro-ecological impacts:

1. As pastures in woods and in meadows are abandoned, animal breeding relies more on crop-based consumption, therefore posing a threat to food sovereignty.

2. As forests are abandoned also as a source of fuel, the risk of wildfires is increased.

3. As meadows are abandoned and afforestation processes initiate, landscape heterogeneity decreases, therefore creating a loss of habitat differentiation and of bio-cultural heritage.

4. As work animals are substituted by machinery, more energy inputs are required for farmland labour that replace internal reuses that integrated funds one another in complex landscape mosaics.

5. As less ruminants in livestock composition, further competition for cropland main produce is exerted, because straw as a by-product can hardly be digested.

6. As livestock density increases –most of them live now in densely populated feedlots so that we can name this process "urbanization of livestock"— management of slurry implies groundwater pollution. The Nitrogen balance of our analysis shows for 28 municipalities an

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excess of 170kgN/ha of cropland, particularly in the Vallès and Maresme counties—a widespread case in Catalonia [53].

7. As more meat in our diet, health problems and hazards increase, from high cholesterol to cancer [5] (World Health Organization, 2015), which means that consumption of red meat should be reduced in Western countries by 78% (that is by 113g/day) in order to meet recommendations from WHO [55].

By considering multi-scalarity at the geographical level we observe a process of county specialization in certain crops or functions that makes even harder to resolve the before mentioned dysfunctionalities in the land-livestock-cropland nexus within the BMR. The Shannon-Wiener index shows how landscapes in the seven counties have become less heterogeneous. Moreover, the adaptation of the index accounted on how heterogeneously funds are distributes indicates that agroecosystems of the BMR are also less functional. Tables 3 and 4 show that both cropland land and livestock were less evenly distributed in 2009 –with Alt Penedès concentrating most cropland and Vallès Oriental most livestock— while urban land, woodland and population (table 5) were more evenly distributed.

The growth in urban area [23] is common to Mediterranean cities and, because of the important role played by county capitals, it assumes the form of polycentric urbanism [9] in which Barcelonès's share of urban area has gone down from 36% to 15%. But it has come at the cost of agricultural abandonment in all counties, implying widespread afforestation and agricultural specialization: forest transition has occurred at all scales, from four municipalities within the BMR [57, 38] to Catalonia overall [11].

Local specialization and economies of scale in detriment of landscape and agricultural multi-functionality [25, 56] have effects on the nexuses between farming population, total population, cropland area, livestock units and available power capacity. They show a joint evolution that quantifies from a landscape agro-ecological perspective the industrialization process.

Vineyards in Alt Penedès (that is a specific agricultural category for a specific county) constitute 34% of BMR total cropland area, which is the only case of cropland growth. Similarly, livestock has moved from large urban centres to the periphery, and pigs in Vallès Oriental constitute 35% of BMR total LU500. Moreover, its population of nearly 100,000 pigs was concentrated in only 111 factories when, in 1999, they were 262. Two phenomena of productive specialization and territorial concentration resembling industrial districts rather than optimizing agroecosystems and landscapes potentials. From the landscape perspective, table 3 shows that landscape functional structure (understood as a heterogeneous and well connected land-matrix) has also decreased as the Shannon Index applied to non-urban land-uses and average loss in ecological connectivity index [43] measured at municipal scale show.

4.3. From organic agriculture to landscape agroecology

The analysis just presented widens the spectrum for the meaning and understanding of landscape agroecology: not only organic agriculture is necessary but, since agricultural activities are imprinted on the landscape, it is important to analyze the effects of entire agroecosystems, with its components not taken in isolation but well integrated between them. Advocating for organic vineyards or meat is important, but even more so is to look at the landscape effects of widespread monocultures, or at the relationships between agroecosystem funds and the agro-ecological opportunities to have multi-functional vineyards and pasturing livestock. Agro-ecosystems are living funds, their sustainability is related to the capacity organisms have to maintain themselves far from entropic decay. That is why internal agroecosystem biomass recirculation can explain a lot. Tello et al.'s approach (2016) linked to landscape analysis [41, 42] is paving the way for a new perspective in landscape agroecology. Here, the double flow of internal biomass recirculation between the land and the livestock sub-systems needs

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balancing, not only in the dimension of the incoming and outgoing flows, but also in the diversity of land uses and animal typologies that are involved, so that dependence on External Inputs is minimized and the agroecosystem is not dysfunctional and resembles more a sustainable organism [33].

A key issue is to consider multi-functionality at multiple scales. In this paper we have introduced and combined the landscape level, the agricultural land level, the livestock composition, cropland products and by-products. Finally, an external element that becomes also very important to understand dynamics in landscape agroecology is the change in diets, which –together with a discussion on the typology and degrees of needs satisfied by agroecosystems— remains an issue for further quantification that, in this paper, is kept only at the qualitative level. [66, table 5.1] show changes in Catalan diet between 1956 and 1999 in which caloric and fresh weight consumption of meat, eggs, milk and cheese have both gone up by more than 90%. In 2009 animal products constituted 24% in weight and 35% in expenditure of the average Catalan household food budget [18]. Marco et al. (2017) relate the arrival of gas bottles for cooking with abandonment of forest extractions and the increased dependence on fossil fuels, and in the same vein [36] shows how wood-crops have lost multi-functionality primarily because pruned branches are not used as FP today. This analysis is not covering the domestic need for cooking, neither for space heating given the boundary limits of our analysis. However, would that issue be considered on this study, then energy inefficiencies would have been even greater as a result of further dysfunctionalities in the agroecosystem and population nexuses.

The increase in Livestock EROI at the expense of a sharp fall in Land EROI can be explained because a major shift has occurred with the combination of industrialization of agriculture and dietary change. In traditional agriculture livestock husbandry was complementary to farming land, but now the organization of entire agroecosystems is only centred on increasing livestock productivity in terms of meat, milk and eggs. Land EROI has decreased mainly because of mechanization -which can be seen as an efficient way of animal husbandry focused solely on fattening animals for protein intake, which can be marketed, rather than on work animals whose role was multifunctional (draught power and manure, wool, leather, horn as well as food) and helped a lot to close the agroecosystem's reproductivity. Pastures in meadows and forests are abandoned because moving animals to and from them would make them burn too many calories, slow their pace of growth diminishing this linear single-minded productivity and raise prices of animal products. Soil fertility is maintained with the application of energy inefficient synthetic fertilizers while at the same time, but in other distant parts of the agroecosystem, the water table is polluted because of excessive Nitrogen from slurry only because it is highly inefficient to move these diluted nutrients to the soils where aremost needed, i.e. from Vallès Oriental to the irrigated horticulture of Baix Llobregat.

Thus, with the multi-functional agriculture of 1956 livestock was at the service of the land(scape): it was moving nutrients from pastures to cropland, maintaining landscape mosaics and working in cropland. In the 2009 case livestock fattening has been disintegrated from agriculture and concentrated into a linear industrial process that has becomedisproportioned in the size of its fund elements, and we observe that the resulting land(scape) is at the service of livestock. Table 6 and the growth in feed-oriented crops show how the productivity gains of the green revolution have been absorbed mainly by livestock feeding, which is using up most of green crops produce (from 48 to 76 GJ/ha), while increases in food-oriented FP have been minimal (from 11 to 14 GJ/ha). Considering cropland area loss and population increase, we can claim that the provisioning ecosystem services from land have dramatically decreased as a result.

In summary, it is necessary to resolve the trade-off between economic viability and land(scape) requirements and animals play a key role in this. Nor they can be too many, as in the 2009 case, neither agro-ecosystems can do without them, particularly when: a) soil fertility needs to be maintained via the nutrient shift from pastures to cropland –which depends on population density and available cropland— and/or b) bio-cultural heritage of traditional agriculture, like the Mediterranean landscape

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mosaic, needs to be preserved in order to maintain support, regulating and cultural ecosystem services as well.

Modern cereal varieties tend to be short-stemmed in order to maximize the grain/straw ratio so that, in principle, there is less need for straw-digesting ruminants. However, these varieties show lower Net Primary Productivity –hence less carbon sequestration potential-- [8], can be less nutritional than traditional long-stemmed varieties, and reduce associated biodiversity such as certain bird typologies which find shelter in tall straw cereal crops. As a consequence, these traditional varieties that in terms of grain produced are economically less efficient actually perform better with respect to carbon sequestration, water efficiency, nutritional values, associated biodiversity and potentially contribute to higher farm animal diversity and lower competition for cropland main produce.

A proper assessment of the energy efficiency of work animals compared to small and large machinery goes beyond the scope of our paper, and is a complex issue. Work animals are ruminants, so that some metabolic benefits of re-introducing them are connected to the point previously made; furthermore, in traditional rural housing systems they have often been placed underneath the sleeping rooms, so that they were a source of heat in the winter; have a lower power capacity than machinery, both for working land and as transportation means, and finally they reproduce themselves and do not require an industrial system for their re-production. On the other hand machinery can be turned off when not needed and, form the economic perspective is an important labor saving technique: once more, the energy vs. economic efficiency trade-off has favoured the adoption of the less multi-functional solution.

Another not yet explored issue, and in line with Scheidel and Gerber's proposal of bridging analysis of social metabolism with needs theory [54], is the one relating agrarian social metabolism with the amount of needs satisfied in different societal contexts: a fully organic system was not only more energy efficient per se, but in that context of a frugal societal it allowed for the full satisfaction of dietary, transportation and domestic heating needs. Instead the agro-industrial regime within a consumerist society implies that less of societal needs are satisfied from nearby agroecosystems, and therefore the metabolic stress is shifted to other places or to future generations. Notably, in the food vs. fuel dilemma the case of agro-fuels relates the societal need of transportation with political ecologies of land grabbing [4] and a metabolic shift to distant places; the case of domestic space heating –satisfied with the use of fossil fuels instead than local biomass- exemplifies a metabolic shift to future generations.

5. Conclusions

This paper has analysed the unsustainable path undertaken by agriculture in the BMR in the process of agricultural industrialization. The economic benefits of specialization in terms of increased labour and land productivity, particularly in the livestock sector, imply significant environmental costs in terms of energy inefficiency, loss of multi-functionality and reduced product diversification. From a circular bio-economy perspective restoring abandoned cropland, shifting livestock from feedlots back to pastures, and rescaling livestock densities are first-order priorities. From a sustainability perspective, change in diets is also very much required, particularly for the incompatible trade-off with population growth.

The application of the Multi-EROI method within MuSIASEM, and with spatial land-use metrics is a powerful methodological approach. In particular, our application of Energy-Landscape Integrated Analysis sheds new lights on landscape agroecology. We have shown how the industrial model has broken the nexuses between agroecosystem funds, something that constitutes the hard core of serious sustainability problems. Not only a more energy efficient agriculture is required, such as organic agriculture, but this needs to be sustainable from the landscape agroecological perspective. This requires that internal flows are highly integrated again between those funds across different land-uses, livestock, land uses and population work in synergy with each other.

If landscape structure and functions are to be well kept sustainable, farm systems require an agro-ecological approach in a way that goes beyond organic agricultural practices considered in isolation from their territorial effects. This becomes the main task for agri-food sustainability: a step forward from organic farms to agro-ecological territories where the main biophysical cycles will begin to close [81].

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