Beyond Chayanov: A Sustainable Agroecological Farm Reproductive Analysis of Peasant Domestic Units and Rural Communities (Sentmenat; Catalonia, 1860)

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1. Introduction

Increasing food demand in a world subject to global environmental deterioration raises the challenge of designing more sustainable agricultural systems capable of maintaining food production within appropriate biophysical limits to guarantee ecological functions. At the same time, growing demands claim to relocate agri-food chains to improve the sustainability of agroecosystems (Sayer et al., 2013), and to rethink land-use planning and rural development programmes linked to nature conservation policies (Stoate et al., 2009). New plans and programmes aimed at tackling this current food–biodiversity dilemma require new indicators and models to combine all these dimensions and approaches, as well as the democratization of governance in order to implement effective solutions (Moragues-Faus and Morgan, 2015; Tello and González de Molina, 2017).

In recent decades, we have witnessed agroecosystems' lack of sustainability with regards to energy and material efficiency losses which, in turn, has led to the increasing replacement of ecosystem services (soil fertility, pest and disease control) by industrial fossil-fuelled external inputs (Giampietro, 1997; Gliessmann, 1998; Leach, 1975; Pimentel et al., 1973). Behind current agricultural degradation and eco-inefficiencies (Cardinale et al., 2012; MEA, 2005; Padró et al., 2017) there are ideological constructs that concern the core of capitalism. Mainstream neoclassical economics considers land and labour only as production factors (Polanyi, 1944). However, when we do not consider them solely as commodities, we realise that they are neither static nor permanent resources, nor two variables of a production function isolated from one another. Ecological Economics is an alternative paradigm that attempts to return to an organic conception of labour, land and other natural resources by considering them as a living interrelated whole from a substantive and holistic perspective (Gerber and Scheidel, 2018; Gerber and Gerber, 2017).

Whether a resource is inanimate or living matters. As Georgescu-Roegen (1971) pointed out, the ultimate aim of agriculture is not only to produce useful biomass but also to reproduce the funds required to maintain the process. Therefore, in order to pursue its coproduction with Nature, agricultural systems have to account for the full costs of their own reproduction in biophysical terms

(Guzmán et al., 2009; Van der Ploeg, 2014). In this regard, the approaches and methods of social metabolism are useful for shedding light on these multiple costs (Haberl et al., 2004).

Nonetheless, social metabolism is at a crossroads, facing two major challenges. First, there is a need to overcome stock-flow analysis by incorporating a fund-flow perspective that recognizes that coproduction with Nature requires reinvesting some specific biophysical flows to ensure the renewal of living funds (Gerber and Scheidel, 2017; Marco et al., 2017). Second, this requires an epistemological step forward to evaluate, integrate and model these fund-flow relationships to reorient agricultural policy, nature conservation and rural development plans (Zhang, 2013). Optimization analysis applied from a novel socio-metabolic and agroecological reproductive standpoint can be a useful tool for such sustainable farming design and land-use planning (Gabrel et al., 2014). To achieve these aims a meeting point between land-use planning and socio-ecological accounting of farming is needed. It is time for ecological economists to develop new optimization models that could identify feasible future scenarios based on what history and present best practices may teach us.

Modelling the functioning of agroecosystems from a reproductive standpoint opens the door for a deeper analysis of the joint functioning of organic farming and agricultural communities, either in past times or at present. We present here a Sustainable Agro-ecological Farm Reproduction Analysis (SAFRA) aimed at devising and planning more sustainable farms and agroecological territories (Wezel et al., 2016; González de Molina and Guzmán, 2017; Stoate et al., 2009; Tilman and Clark, 2014). This linear programming model allows the optimization of land-use distributions based on the need to reproduce three agroecosystem funds (the peasant community, livestock and farmland), by always keeping a set of interactions among them that take into account their biophysical and technological limits.

There are two proposals on which we set the foundations of this model, even though they differ significantly from each other. First, this study is connected with the internal planning of economic peasant units proposed by Chayanov ([1925]1985; Van der Pleog, 2014). Chayanov’s theory of peasant economies began the development of reproductive studies of domestic farming units, by accounting for the amount and allocation of land required according to the components of the family farm, livestock density and cultural practices at stake. However, his approach combined only units of labour time, family needs, livestock intake and farm produce translated into a monetary budget driven by the effort–consumption balance. Here, we incorporate a biophysical dimension to ensure the simultaneous maintenance of a larger range of living funds, such as farmland reproduction (by assessing soil biogeochemical cycles).

Secondly, this research is related to food systems analysis. These studies use optimization analysis to identify the most appropriate distribution of land uses in order to satisfy diets from a local or regional perspective. They assess the impact of diets and the food supply capacity at the local level, within the framework of conventional agriculture, focusing on the consumption side. Although food systems research incorporates optimization analysis from a socio-ecological perspective (Desjardins et al., 2010; Meier and Christen, 2013; Peters et al., 2007; Van Kernebeek et al., 2016), it does not include a fund-flow analysis – i.e. it does not attempt to close the biophysical cycles of funds (Altieri and Nicholls, 2012; Wezel et al., 2016).

Other applications of optimization analysis in designing how to distribute land uses in agriculture are also well known, but so far its application has mainly been limited to monetary accounting (Knoke et al., 2015). Finally, some optimization analysis also appeared as tools to consider the effect of multifunctionality on land uses, although flux interactions among land uses are not been considered (Grabaum and Meyer, 1998; Meyer et al., 2009; Sadeghi et al., 2009; Seppelt and Voinov, 2003; Smit, 1981; Stewart et al., 2004).

As a first step in our research strategy, we modelled the agroecosystem functioning of a local case study before the Green Revolution through an exercise of Applied Environmental History based for the first time on a socio-metabolic optimization model. In this regard, the study of past organic agrarian societies, just before agrarian capitalism fully developed, has two advantages. First, the methodology is much simpler compared to current agro-industrial systems, which depend heavily on external non-renewable resources. Second, the results obtained with this interesting analysis transcend purely historical interests.

Such agrarian economies were still driven by an advanced organic metabolism, where feasible biophysical intensification was mainly restricted to the local or regional level. This led farmers to maintain the integration among the different compartments of the agroecosystems, imprinting complex agrosilvopastoral mosaics in the territory (Antrop, 2005; Fischer-Kowalski and Haberl, 2007; Krausmann, 2004; Marull et al., 2016, 2010). Specialization processes via cash crops tended to push such agricultural systems towards their biophysical limits, and even to disrupt them through degradation processes. Thus, studying past organic farm systems offers useful information on the strategies used by farmers to meet the reproductive needs of all living funds (Tello and González de Molina, 2017; Tittonell, 2014), which could be useful references for developing a new sustainable farm metabolism today.

Although the main objective of this study is the theoretical, conceptual and mathematical definition of the SAFRA model, secondary objectives are pursued by applying it to a past organic agricultural system. First, we look for the multiple synergies and trade-offs which only arise by considering the funds' reproduction altogether compared with working them in isolation. Second, we investigate how farming strategies were aimed at satisfying contrasting goals that led to different funds' composition and reproduction.

In the second section we outline the conceptual approach used to study a past advanced organic agricultural system. The third section describes the features of the local case study. The fourth presents the methodology of our socio-metabolic optimization model. After running the model, the fifth section presents the results. Then, in the sixth we compare the scenarios obtained with the actual distribution of land uses by every farm in the case study, and to other Chayanovian models. We conclude in the seventh section by outlining the main findings and conclusions regarding the methodology and the functioning of advanced organic management of agroecosystems.

2. Conceptual development of the Sustainable Agroecological Farm Reproductive Analysis (SAFRA)

2.1 A socio-metabolic model for agroecosystems' reproductive functioning

In order to improve agroecosystem planning, a new modelling approach is needed to tackle the auto-reproducible funds of farm systems. This means understanding how land, labour and natural resources can be de-commodified and sustainably managed within their own constraints. Funds are understood as those 'elements that are part of a process, which provide services for a certain period but are never physically incorporated in the product', as defined by Georgescu-Roegen (1971). Specifically, those of a biological basis are auto-reproducible funds whose maintenance requires regularly reinvesting a certain amount of the biomass taken from the agroecosystem. Disregarding either the limits in the rate and volume of extraction or in the reinvestment required means jeopardizing the agroecosystems' sustainability (Giampietro et al., 2013).

We will consider three main funds: farmers' domestic units, livestock and farmland. The model identifies the conditions required to reproduce them in a specific territory over the timescale of one year. For example, farmers need to maintain their workforce to sustain the flow of labour, which entails two basic material conditions: provision of enough food and fuel, and not exceeding their own work capacity. The same applies to livestock and farmland (the latter assessed through biogeochemical cycles but also based on its capabilities in terms of soil quality or irrigated land). These biophysical constraints, each measured using different meaningful values, determine the range of feasible and technically viable farms that could have existed under the prevailing site-specific historical and biogeographical context.

In this way, the optimization model generates simulated scenarios, either in the past as counterfactual analysis or in the future as prospective scenarios, in a controlled process that integrates all the relevant constraints that ensure the socio-ecological reproduction of funds. The modelling degrees of freedom guarantees that results would be technically viable and agroecologically feasible, avoiding *ceteris paribus* assumptions as the model considers the simultaneous interactions that always take place among the main dimensions modelled. When applying this SAFRA model, and considering the joint reproduction needs and capacities of all these funds, we can identify the potential synergies and trade-offs that arise when they are managed in an integrated manner, and thus determine the composition that optimizes their functioning under a specific goal in a site-specific context.

2.2. How social agencies constrain fund distribution

The biophysical factors considered to date define only the range of possibilities and limits within the agroecosystem e.g. its land-use and labour intensification capacities in a given context. However, land appropriation deeply affected its use and the ensuing organization of farm labour, which entailed other kinds of ruling forces. In addition, we are aware of the difficulties of defining the territorial boundary of an agroecosystem, as there were exchanges of biophysical flows with other areas, and with non-farming social groups. Because of this, to develop a more reliable approach from a societal and institutional perspective, we will consider agroecosystem functioning at the farm-gate and community-level scale simultaneously (Bayliss-Smith, 1982; Gerber and Scheidel, 2018; Gizicki-Neundlinger et al., 2017; Gizicki-Neundlinger and Güldner, 2017; Marco et al., n.d.). This would allow us to understand how agroecosystems could have been optimized under equal access to land, both for domestic units and at municipality level (as the composition of the whole community included different types of domestic units). From a socio-metabolic perspective we have identified three main categories relevant to land-use allocation in farm planning, similarly to the way in which Cronon (1991) defined the ‘first and second nature’ constraints: *i*) biophysical constraints (nature–nature relations), including biotic and abiotic factors present in the farm units; *ii*) cultural factors (nature–society relations), such as the set of technologies and management approaches available in a site-specific context; and *iii*) the prevailing social conditions (relations among people), including all societal constructions (institutional, economic, political or cultural) that affect agricultural practices. Distinguishing between *ii* and *iii* allows counterfactual analysis by identifying how the relations among people (*iii*) affect farm decisions and agricultural development by assuming the potential agricultural practices determined by the cultural and biogeographic context. Therefore, we have adopted herein a counterfactual analysis in the same way as in economic history (Cartwright, 2007;

Fogel, 1964; North, 1961), but by assessing the underlying constraints and relationships through biophysical analysis.

3. Case study: Sentmenat (Catalonia, Spain) c. 1860, a region specializing in vine growing at the dawn of agrarian capitalism

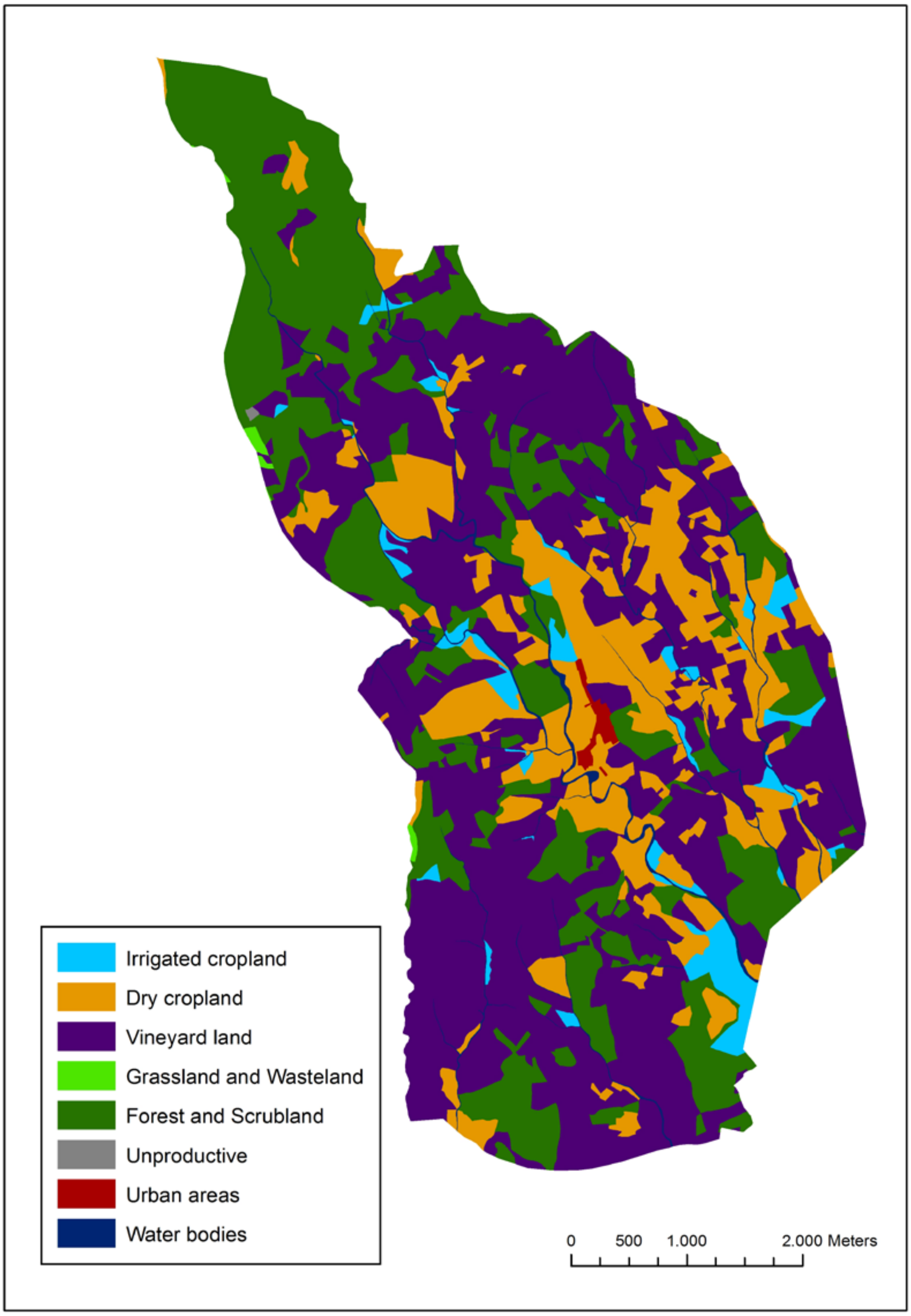
We tested our SAFRA model in the context of an advanced organic agricultural system in the municipality of Sentmenat (Catalonia, Spain), which circa 1860 partially specialized in vine growing. A vast amount of socio-metabolic research has been carried out on this case study (Cussó et al., 2006; Galán et al., 2017, 2016, 2012; Garrabou et al., 2010, 2008, Marull et al., 2016, 2010; Olarieta et al., 2006; Tello et al., 2016, 2012), providing a large and reliable database on the composition of funds and flows at that time (for further details, see section 4.4).

Sentmenat is located on the tectonic boundary between the Vallès plain and the Catalan pre-littoral mountain range. It covers 2,880 ha with wide topological, geological and soil diversity under a sub-humid Mediterranean littoral climate. Rainfall varies between 600 and 800 mm per year, increasing with altitude (Rodriguez Valle, 2003). Figure 1 shows how c. 1860 vines coexisted with dryland polycultures and woods, forming agricultural, pasture and forest mosaics. Population density was 60 inhabitants/km^2 which, according to Badia-Miró and Tello (2014), fitted the optimal demographic conditions for vineyard specialization. Vineyards covered 42% of the total surface area (72% of cropland), and produced some 17,000 hl of wine a year. Although there is no data on vineyard surface area for 1890, when it reached its peak, we know that wine production had increased up to 26,000 hl (Planas, 2015) by the time the *Phylloxera* plague started destroying French vines in the 1860s and ended up devastating those of the Valles in the late 1880s. Very few vineyards recovered from this devastating disease in the study area (Badia-Miró et al., 2010).

Importantly, until 1860 the agroecosystem functioning of Sentmenat was mainly restricted to the regional level from the reproductive view of its funds' maintenance. Local food and firewood needs were still largely met at the regional level (Padró et al., 2017), while livestock requirements and soil fertility maintenance were met at the local level. However there were also links to international

Atlantic markets (for wine exports) and to the inner Iberian Peninsula (for wheat imports). As well, the land entitlements that prevailed in the transition from feudalism to agrarian capitalism, and the ensuing social polarization between wealthy landowners and small vine-growing tenants and labourers, played a major institutional role in this Catalan rural community (Garrabou et al., 2008, 2010; Congost et al., 2015).

Figure 1. *Land uses in Sentmenat circa 1860. Source: Our own.*

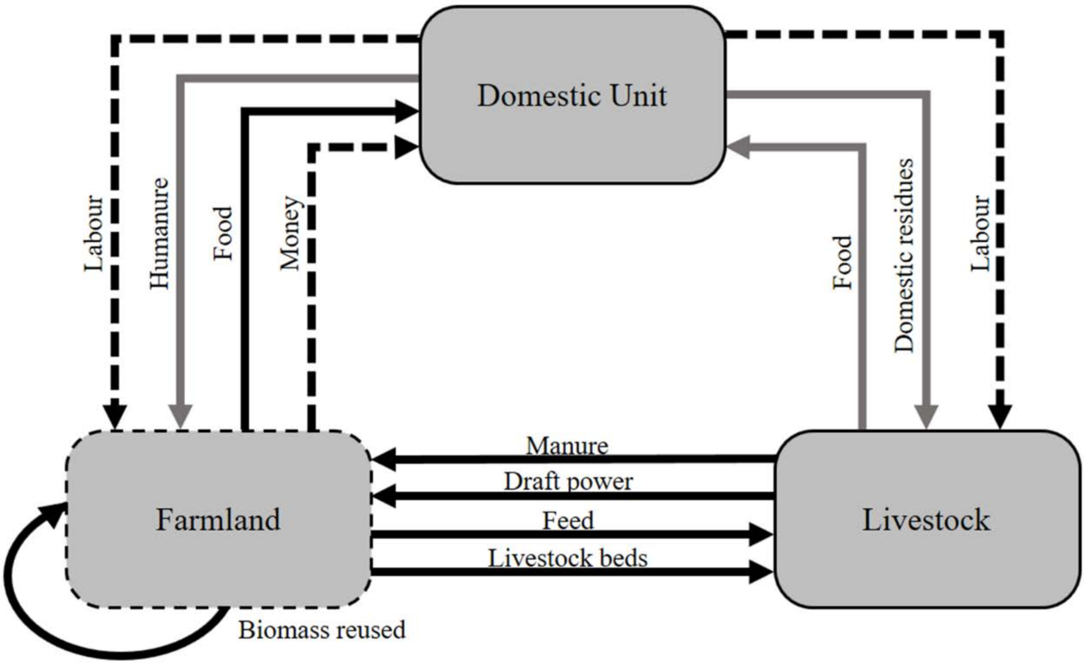


4. Methodology[1]

4.1 General structure of the model

We developed the socio-ecological model based on the ability of farmers and communities to reproduce their basic funds under the prevailing natural and technical endowments from a fund-flow approach (Mayumi, 1991). The funds considered were, as mentioned: domestic units (DU), livestock, and farmland. Using the optimization model we accounted for the multiple interactions (flows) among these three funds in a way that might allow for their reproduction while reaching different optimality when satisfying a set of alternative specific goals (Figure 2).

Figure 2. *Modelling diagram. Source: our own. Squares represent funds and arrows the flows interlinking them. Grey arrows are fluxes constrained as boundary conditions, while black ones are the restrictions calculated with the optimization model. Discontinuous lines emphasize the objective functions to optimize.*



The mathematical procedure for running the optimization model is linear programming. This method achieves the best result by maximizing or minimizing (optimizing) first-degree functions, allowing infinite variables and linear constraints. Once the model is defined, it is run through the

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[1] See Supplementary materials for further details

Simplex algorithm programmed using the Java software Gusek (Bettoni, 2009; Dantzing, 1963). The model comprises main variables (22), secondary variables (128), parameters (3), general constraints (187), specific constraints (68) and objective functions (3). This structure allows for three different kinds of scenario, one for each objective function.

The modelling of all these constraints defines the range of agroecologically feasible and technically viable scenarios (as it ensures the reproduction of all the funds considered under the prevailing cultural practices in the historical and edaphoclimatic context).

As its main function is to define the structure of flows and funds in the agroecosystem, in this site-specific context the number of constraints, variables and parameters would be different for each particular goal adopted. This is because the potential fluxes among funds will depend on the kind of cultural practices that could be available and desirable (livestock types, crop rotations, fertilization practices, etc.).

4.2 Boundary conditions

In order to calculate its size a fund should have to optimize a given goal in a sustainable way, and we considered the size of the other two funds as boundary conditions. This involves checking whether livestock density changes would increase the efficiency of resource allocation in the different scenarios.

We started the process by defining the size and composition of the domestic unit (DU), which entails an important decision that affects the interpretation. The representative family selected supposes a rate of consumers/producers consistent with the average dependence rate of the whole municipality, so as to allow us to extrapolate the DU results at the local level. Indeed, following Chayanov ([1925]1986), we also included five different stages of the family life cycle of this representative DU in order to determine how requirements would change over time, and to avoid underestimating or overestimating the results.

Our representative DU of five people (the average family type in Sentmenat c. 1860) comprised a girl between 0–5 years old, a boy from 5–10 years old, a woman and a man between 18 and 60 years old, and a man older than 60.

4.3 Variables, general constraints and parameters

The main variables, from X_1 to X_{22}, represent the surface area of each land use (see Table 2), although in the programming they were divided by soil quality (including new variables from X_{23} to X_{41}). Secondary variables regarding fluxes were as follows: X-secondary variables ($X_{i,j,k}$) are the fraction of embedded land in the biomass produced by a land use i, and a kind of product or by-product j used in a human activity k; and Y-secondary variables ($Y_{l,m,n}$), which do not represent land but fluxes from another fund l, a kind of product m used in a human activity n. Therefore, there are as many secondary variables as directions flows could take. This supposes, in turn, two kinds of general constraint: *i*) each variable must be a positive number; *ii*) every group of secondary variables is associated with the total amount of land (X_i) or biomass coming from livestock or the DU (Y_l).

As pointed out in section 4.2, the dimensions of DU and livestock heads are boundary conditions. We thus defined a parameter Z that represents the integer number of members in the farm unit. Small livestock numbers depend on the size of the DU (Z), while draught animals depend on the cropping surface through another parameter M, representing its density.

4.4 Specific constraints and data sources

All variables are subject to a number of biophysical constraints expressed by linear inequalities. These constraints are imposed by the conditions required for the agroecosystem reproduction, ranging from obtaining enough food, fuel and money, to feeding livestock and closing the soil biogeochemical cycles, while maintaining the historically prevailing crop rotations. We defined the minimum and maximum feasible ranges of flows for the three funds, which would allow each of them to ensure agroecological reproducibility (minimum for inputs, and maximum for outputs of the fund). Table 1 summarizes the main aspects considered in the optimization model, from which constraints were derived. Regarding DU consumption, we considered basic human material needs as being determined *ex-ante*, and did not consider the improvement of farmers' well-being (Harrison, 1975). Given that we wished to set a threshold for farming family reproduction, and not for how to organize a farm with abundant means of production, we consider this demand to be inelastic.

Table 1. Constraints and main sources considered in the programming model..

Fund	Main flow	Associated funds	Units	Procedure
Domestic Unit	Labour	Farmland, Livestock	Workdays	Twelve inequalities with human monthly requirements of labour for crops, forest and livestock (Garrabou et al., 1992; IACSI, 1879) on the one hand, and the working capacity of the DU on the other (Marco et al., n.d.)
	Food	Farmland, Livestock	Kg of fresh matter	Eight inequalities, one for each main product typology in the diet (wheat, legumes, olive oil, etc.), where production must be higher than requirements, calculated from the typical diets in the region in the mid-19th century (Cussó and Garrabou, 2012)
	Fuel	Farmland	Kg of fresh matter	Inequality considering the need for fuelwood from forest and woody crops in order to cook and heat the house, based on a review of sources (Marco et al., forthcoming). Inequality limiting the use of vine-wood according to its low latent heating (Colomé, 2016; personal communication)
	Money	Farmland, Livestock	Pesetas	Inequality to ensure enough money for the reproduction expenses coming from other Catalan Chayanovian-reproductive studies. We considered costs relating to clothing and footwear (Colomé, 2015), the rent for housing (Colomé, 1996 and Vicedo et al., 2002), and the amortization cost of farm implements and the maintenance of barrels for wine producing (Colomé, 1996). We also considered the costs of paying the royal land, housing and livestock cadastral taxes, as well as the municipal taxes according to the *Distribution of Personal Wealth in Real Estate Ownership of 1852 in the Barcelona Province* (Library of the University of Barcelona, reference 146-1-II/13). All these costs must be lower than the surplus produced via farm sales in the local market, assessed through the prices given in the *Estudio Agrícola del Vallès* (Garrabou and Planas, 1999)
Livestock	Feed	Farmland, Domestic Unit	Metabolizable energy	Six inequalities, one for each species of livestock (sheep, mule, hens, etc.), in order to ensure enough metabolizable energy to meet their requirements (assessed by Church, 1984), through the consumption of products and by-products from farmland and domestic residues as well. We also introduced five more inequalities to guarantee that feed ratios were reasonable based on animal physiology criteria (FEDNA, 2010).
	Stall bedding	Farmland	Kg of fresh matter	Inequality ensuring that by-products used for stall bedding (straw and stalks) were suitable for the animal beds (Cascón, 1918; Soroa, 1953)
	Draft power	Farmland	Workdays	Inequality where total amount of labour required for cropping practices has to be lower than the available workdays from draught animals (Garrabou et al., 1992; IACSI, 1879)
Farmland	Soil biogeochemical cycles	Domestic Unit, Livestock	Kg of nitrogen, phosphorus and potassium	Fifteen inequalities (five land covers and three nutrient balances for each nutrient) assuming that biogeochemical fluxes are closed at the farm level using humanure, animal manure and burying biomass (from cropped areas but also from forests). Nutrient balances were calculated following González de Molina et al. (2010), composition of humanure according to Gootas (1956), manure according to the ASAE (2000) and the nutrient composition of biomass according to a previous meta-analysis (Galán et al., 2016; Guzmán et al., 2014; Tello et al., 2012).
	Soil qualities		Hectares	Two inequalities ensuring that fractions of soil qualities I and II (there are III in total) are not higher than the total share at the municipal level according to the cadastre.
	Crop rotations		Hectares	Fifteen equations, four for irrigated land, five for herbaceous dryland and six for herbaceous grains intercropped with olive trees, in order to reproduce the same rotations described in the *Estudio Agrícola del Vallès*.
	Irrigated land		Hectares	Inequality constraining the total surface area of irrigated land to the same share recorded in the municipality c. 1860 in the cadastre.

Sources: See the right column.

The data used to set the constraints was based on an array of documentary sources such as the Population Census, Cadastral Map, and Land-Use Register (*Amillaramiento*). The *Estudio Agrícola del Vallès* (Garrabou and Planas, 1998), a manuscript written in 1874 that provides a detailed description of the common agrarian practices performed , their frequency and their distinct local specificities, was also fundamental as contains in-depth knowledge on the agrarian metabolism in this area. Data on yields by land-use, soil quality and rotations given in the *Amillaramiento* was a 5-year average to avoid inadvertently selecting an extreme-weather year (Table 2). These sources ensured the quality of the data used in the model, which has been reinforced through multiple cross-checking done by the many researchers who have used this case study as a test bench (Cussó et al., 2006; Galán et al., 2017, 2016, 2012; Garrabou et al., 2010, 2008, Marull et al., 2016, 2010; Olarieta et al., 2006; Tello et al., 2016, 2012).

Regarding data on the technical coefficients required to turn fresh weights into dry weights, energy and nutrient contents according to the composition of each biomass flow, we took advantage of several meta-analyses conducted within the international project *Sustainable Farm Systems*, and others that have standardized from a historical point of view the nutrients and moisture of products and by-products, livestock and human requirements and manure amounts and compositions detailed in Table 1.

Table 2. Registered land productivity and estimated by-products according to soil quality (SQ), in kg/ha, fund direction of flow and main variable in parenthesis. DU indicates Domestic Unit, L to livestock and F for farmland. Source: our own.

	Crop or land use (main variable)	Product	SQ1	SQ2	SQ3	Direction
Vegetable gardens	**Vegetables (X_1)**	Vegetables	5,070			DU
		Straw	5,342			L
	Fresh fruits (X_2)	Fruits	4,148			DU
		Firewood	2,475			DU
	Nuts (X_3)	Dry fruits	525			DU
		Firewood	2,847			DU
Irrigated	**Wheat (X_4)**	Grain	1,242	1,023	731	DU
		Straw	2,889	2,433	1,825	L+F
	Corn (X_5)	Grain	1,348	1,075	802	L
		Stalks	1,044	835	627	L
	Hemp (X_6)	Fibre	1,213	1,104	996	DU
		Stalks	1,477	1,354	1,231	L
	Beans (X_7)	Beans	1,078	853	640	DU+L
		Straw	1,695	1,378	1,060	L
Rain-fed annual crops	**Wheat (X_8)**	Grain	1,169	877		DU
		Straw	2,737	2,129		L+F
	Associated wheat (X_9)	Grain	877			DU
		Straw	1,521			L+F
	Corn (X_{10})	Grain		501		L
		Stalks		783		L
	Rye & wheat mixture (X_{11})	Grain		424	636	DU
		Straw		1,176	1,617	L+F
	Barley (X_{12})	Grain			439	L
		Straw			1,096	L+F
	Fodder (X_{13})	Fodder		6,754		L
	Potatoes[2] (X_{14})	Potatoes	1,679/1,250	1,215		DU
		Straw	1,020/784	765		F
	Beans (X_{15})	Beans	658			DU+L
		Straw	1,060			L+F
	Vetches (X_{16})	Vetches			658	L
		Straw			954	L+F
	Lupins (X_{17})	Lupins			585	L
		Straw			954	L+F
Woody Crops	**Olives (X_{18})**	Olive oil	273	202	141	DU
		Browsing	796	590	413	L
		Pomace	1,205	893	625	L
		Firewood	1,628			DU+F
	Vines (X_{19})	Grape juice	2,142	1,683	918	DU
		Pomace	912	717	391	L
		Firewood	2,442			DU+F
		Leaves	1,250			F
Extensive uses	**Fallow (X_{20})**	Pasture	1,523			L
	Pasture (X_{21})	Pasture	3,947			L
	Forest (X_{22})	Firewood	5,438	4,078	2,719	DU+F
		Pasture	1,523			L
		Oak acorns	187			L

Sources: the same listed in Table 1 and given in the text.

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[2] Potatoes were grown in first quality soil, both in the rotation of herbaceous dry land (1,679 kg/ha) and olive dry land (1,250 kg/ha)

4.5. Objective functions

After setting the whole range of constraints to define the biophysical and technical limits of the agroecosystem considered, the last step before running the model was to define objective functions. We optimized the resulting model according to the goals farmers might have adopted under the prevailing conditions. Therefore, we considered three functions that characterize different farming goals: *i*) land-saving: the minimum surface area required to ensure reproducible exploitation, called the Minimum Reproduction Unit (MRU; Eq. 1); *ii*) labour-saving: the area required for funds' reproduction while minimizing total labour, or the Peasant Reproduction Unit (PRU; Eq. 2); and *iii*) commercial maximization: the maximum sustainable vine-growing area or Maximum Sustainable Specialization (MSS; Eq. 3).

$$min\left(\sum_{i=1}^{i=22} X_i\right) \text{ (Eq.1)}$$

$$min\left(\sum_{i=1}^{i=22} W_i X_i + f(X_i, M, Z)\right) \text{ (Eq.2)}$$

$$max(X_{19}) \text{ (Eq.3)}$$

where X_i is the area of each land use, W_i the number of workdays required for each land use, $f(X_i,M,Z)$ is the number of workdays associated with fertilization practices resulting from the model, and X_{19} is the vineyard area.

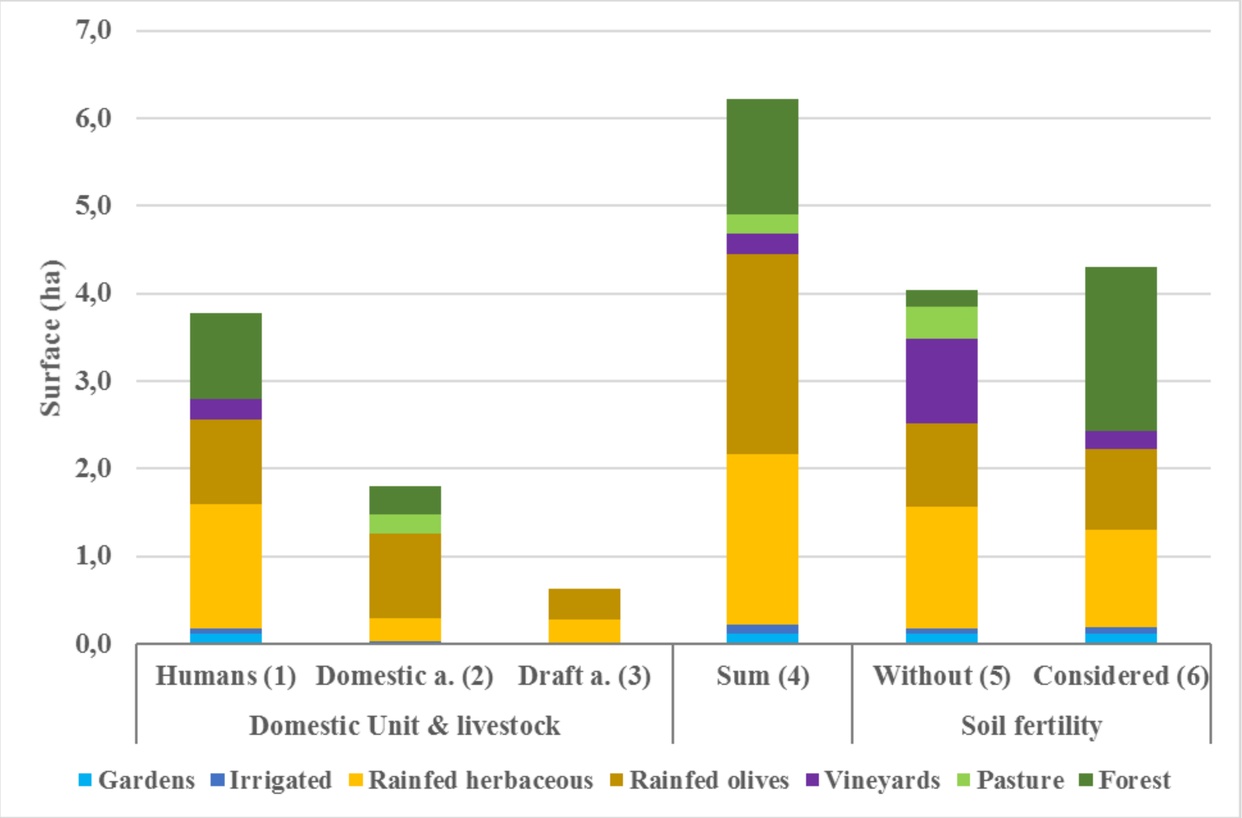
Each farming goal will result in a different type of scenario (whether MRU, PRU or MSS). However, relying on the literature and because of the actual relevance of historical vineyard specialization in the study area, we considered three different sub-scenarios for MSS. While MSS1 will be restricted by all the specific constraints of section 4.4, MSS2 will consider the ability to import labour from outside the farm/municipality (thus constraints regarding to human labour will not be applied), as was actually happening in the area (Garrabou et al., 2015). Finally, together with considering that labour was not to be satisfied locally, MSS3 will consider the ability to import a share of the diet from outside the system boundaries, as historical sources support around 26% of staple grains was locally imported, mainly in the form of wheat coming from inner Spain (Garrabou, Cussó & Tello, 2007: 201). All these scenarios will be modelled assuming equal access to land. This methodological assumption is key to then compare the simulated results with the actual ones in a way that reveals the role played by inequality to shift the real configuration away from those optimal scenarios.

5. Results

5.1. The metabolism of a Minimum Reproduction Unit

The first objective function minimizes the land requirements of the farming population (Eq. 1) to assess the existing capacity for sustainable land-use intensification by identifying the minimum land cost to maintain the three funds. This strategy seeks to accommodate as much of the population as possible on the available land. The results are shown in Figure 3. In order to meet the food, fuel and income requirements of the domestic unit, the surface area needed would have been 3.77 ha (case 1). Notice that, in this case, the DU would have had to buy meat and fertilizers, as there would not have been domestic animals neither soil nutrient replenishment.

***Figure 3.** Scenario of MRU by goals, for a family of five people.*[3] *Source: Our own.*



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[3] As you can see in this figure, we present the three funds as separate goals. While in the case of DU and animals (separated by draft power and other domestic animals) we can analyse them separately, fertilization has intrinsically not a cost on surface; you can calculate the increase of the total land cost due to fertilization only with respect to other requirements.

For livestock reproduction, which would have included two sheep, a pig and some chickens and rabbits as assumed in the estimated historical average of a domestic unit, an additional 1.81 ha would have been required (case 2). The high proportion of the previously calculated area that this entails reflects the required rotation with dryland olive groves, and is consistent with the need to produce fodder legumes (e.g. lupins) to feed the livestock (Roca, 2007). Feeding the share of annual feed that corresponds to the 0.25 mule required for ploughing would have entailed an additional 0.63 ha (case 3). Therefore, to guarantee the reproduction of both the DU and livestock funds, and if we make the sum of these three surface areas cumulative (i.e., if each one was devoted to fulfilling a single goal), our standard DU would have required a total of 6.21 ha of farmland (case 4).

However, by taking advantage of the existing multipurpose character of peasant land and livestock uses (e.g. farmers used forest for pasture and for firewood and timber provision), together with the possibility of using crop by-products for animal feeding, the minimum area actually required for such a family farm would have been reduced from 6.21 to 4.04 ha (case 5). This demonstrates the existence of land-use synergies among funds.

Feeding livestock in ways that did not compete with human food also played an important role on the total surface area required. While in the first run of the model (cases 2 & 3) animals would have been fed with main crop products, such as corn or vegetables, in the second run (case 5) animal intake would have relied on crop by-products such as straw or pomaces and on natural pastures (Table 3).

Other fund-flow synergies between different compartments of the agroecosystem appeared when soil fertility maintenance was taken into account. As a result, land-use synergies and livestock multi-functionality reduced the total area required to reproduce the farm unit by 54%. At first glance the maintenance of nutrient cycles in cultivated soils did not significantly affect the total useful area needed: surface only increased by 7%, from 4.04 to 4.31 ha (case 6; Table 3). However, this increase of 0.27 ha would also have been associated with a change in the use of pastures in favour of forest as a nutrient supplier, as well as the restructuring of land uses according to soil quality.

Table 3. Main results of the scenarios by fund. Source: Our own.

		Units	MRU	RPU	MSS(1)	MSS(2)	MSS(3)
Farmland	Vegetable gardens	Ha	0.12 (3 %)	0.12 (2 %)	0.12 (1 %)	0.12 (1 %)	0.12 (1 %)
	Irrigated		0.07 (2 %)	0.09 (2 %)	0.00 (0 %)	0.13 (2 %)	0.13 (2 %)
	Herbaceous crops		1.12 (26 %)	1.55 (26 %)	1.86 (23 %)	0.99 (12 %)	0.51 (6 %)
	Olive groves		0.93 (22 %)	0.23 (4 %)	0.35 (4 %)	0.29 (3 %)	0.26 (3 %)
	Vineyards		0.19 (5 %)	0.81 (14 %)	2.12 (26 %)	4.77 (58 %)	5.43 (66 %)
	Pastures		0.00 (0 %)	0.94 (16 %)	1.29 (16 %)	0.87 (11 %)	1.30 (16 %)
	Forest		1.88 (44 %)	2.09 (36 %)	2.51 (30 %)	1.09 (13 %)	0.50 (6 %)
	Total surface		4.31	5.83	8.25	8.25	8.25
	Humanure	kg N	22.10 (32 %)	22.10 (32 %)	22.10 (22 %)	22.10 (19 %)	22.10 (19 %)
	Manure		22.24 (32 %)	21.98 (32 %)	23.79 (23 %)	27.71 (24 %)	27.03 (23 %)
	Burying biomass		25.77 (36 %)	24.98 (36 %)	56.27 (55 %)	66.46 (57 %)	68.55 (58 %)
Domestic Unit	Labour	workdays	434 (68 %)	367 (57 %)	467 (72 %)	555 (86 %)	564 (85 %)
	Labour April		29 (55 %)	24 (46 %)	47 (99 %)	76 (144 %)	84 (159 %)
	Labour October		17 (38 %)	21 (49 %)	35 (100 %)	67 (154 %)	73 (168 %)
	Gross revenues	*Pesetas*	984	979	1,045	1,419	1,434
Livestock	Pasture	kg ms	1,604 (37 %)	13,585 (73 %)	17,452 (73 %)	15,124 (56 %)	16,061 (58 %)
	By-products		2,714 (63 %)	2.587 (16 %)	4,906 (22 %)	10,333 (41 %)	8,541 (35 %)
	Grains and forages		0 (0 %)	2.436 (13 %)	1,595 (7 %)	1,767 (6 %)	2,921 (11 %)
EROI	FEROI	Adim.	0.43	0.49	0.31	0.24	0.23
	FEROL		33.80	50.97	39.31	24.84	24.09

Source: Our own, from the sources given in the text and previous tables. EROI: Energy Return on Inputs; FEROI: Final EROI; FEROL: Final Energy Return on Labour; see Tello et al. (2016). Adim means adimensional values.

5.2 An extensification scenario based on the minimum labour needed for a Peasant Reproduction Unit (PRU)

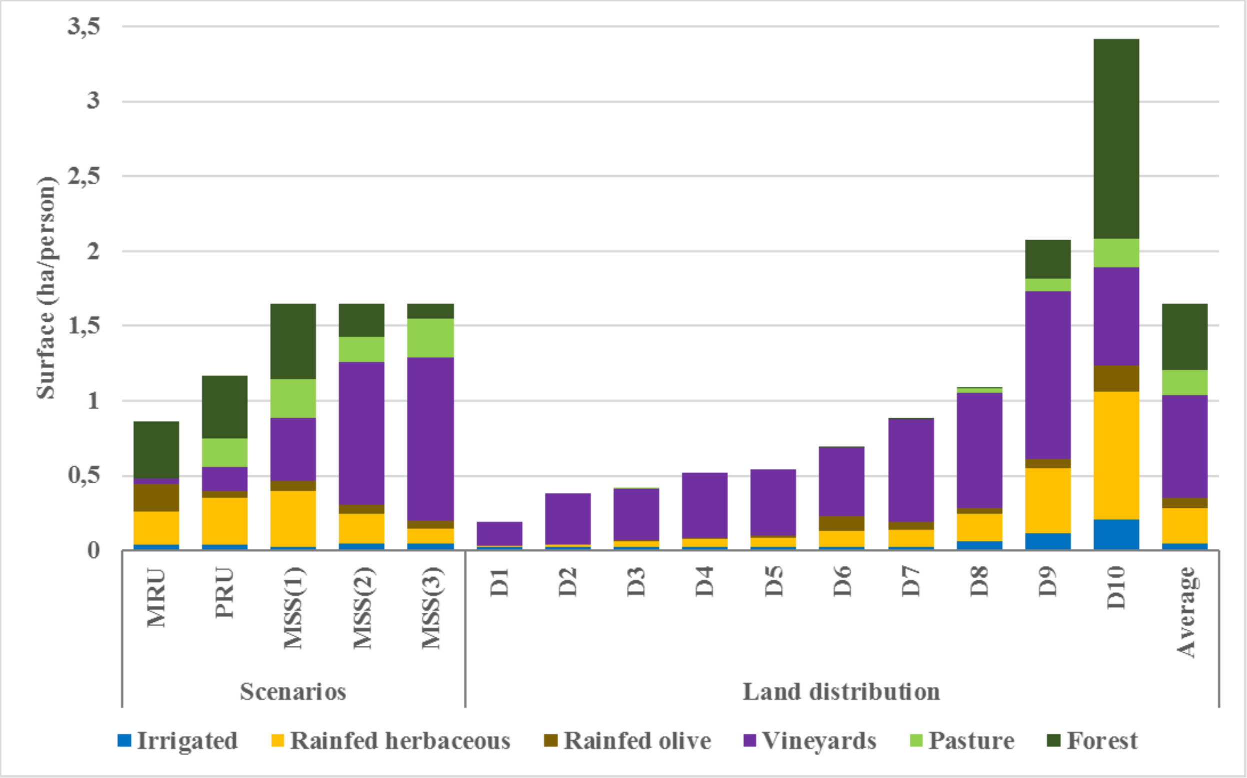
The land surface area required to minimize the labour applied under a PRU scenario would have been 5.83 ha for a five-person family in Sentmenat c. 1860, 29% higher than for a land-saving MRU strategy (see Figure 4 and Table 3). In addition, this labour-saving strategy would entail changes in land use patterns. As expected, more extensive use increased the surface under pasture and forest by over 52%. Vineyards increased by 14%. The latter illustrates their role as a cash crop, in contrast with the MRU scenario, in which olive groves played a major role. Cereal rotation associated with olive trees yielded higher gross revenues than vineyards, but required 87% more labour per hectare. Therefore, the aim of minimizing labour costs and achieving higher net incomes favoured the growth of vines instead of olive trees.

5.3. The Maximum Sustainable Specialization (MSS) scenario to expand the vine-growing strategy

By means of the third scenario, we calculated what the highest share of vineyard would have been under equal access to land while ensuring the reproduction of funds, and identifying the factors limiting the further expansion of vines. This allows us to go deeper into the analysis of the role specialization in vine growing played in our case study. Figure 4 shows the results obtained using additional assumptions. The average farm size for five people would have been 8.25 ha/DU. If we consider the need to satisfy the required reproduction flows of the three funds (MSS1), the highest share of land devoted to vines would have been 26%, far below the 42% recorded in c. 1860. In this case labour availability appears to have been the limiting factor to vineyard specialization, especially during the key months of October (harvest) and April (leaf removal) (Table 3). If we then consider the feasibility of hiring external labour in these peak seasons, as was the case in Catalonia at that time (Garrabou et al., 2015), vineyard specialization would increase to 58% of the cropland area (MSS(2)). If we wonder why vine growing did not reach this level in 1860, we immediately see that it would have been necessary to clear more forestland, brushwood and pastureland. About 22% of the total surface was forest and pasture at that time, and cultivating an additional 416 hectares would have involved a huge amount of labour, and an important opportunity cost in terms of firewood, timber, wood pasture and nutrients for cropland. Here, too, comes the role of inequality: wealthy landowners preferred to save labour and wage costs, while maintaining their own supply of firewood and pasture, to avoid too risky market dependence (Garrabou, Cussó & Tello, 2007; Pascual, 1990; Bhaduri, 1986).

Finally, in model MSS3, crops would only meet the fraction of the local diet consisting of vegetables and fruits. Vineyards could have been grown on 66% of the whole municipal area (MSS3), but the village would have had to import 44% of its diet, mainly in the form of wheat and potatoes.

Figure 4. *MRU and RPU scenarios, MSS according to the limiting factors considered and actual land-use distribution by deciles of surface (for 191 farms) and average value c.1860 in Sentmenat. Source: Our own.*



6. Discussion

6.1 Landscape synergies and trade offs

As it has long been stressed in the study of carrying capacities, defining biophysical limits for the anthropogenic use of ecosystems has to explicitly consider which goal is going to be optimized (Murray, 2009). This is something that our optimization model can assess with the different kinds of goals, in order to determine the diverse area requirements and land use patterns required. The comparison between our counterfactual SAFRA scenarios and the actual situation makes the reliability of linear optimization models apparent. They offer a means of socio-metabolic accountancy that is able to reveal the different configurations that agroecosystems and land uses could have had, all sustainable, depending on the main goals farmers might have adopted.

The Minimum Reproduction Unit (MRU) revealed that the cost maintaining the three funds altogether, was only 0.54 ha above the 3.77 ha required to maintain the DU alone, i.e. an additional 14% of surface (figure 3). Therefore, here comes the meaning of our first main result: despite there is a

Land Cost of Agrarian Sustainability (i.e. the amount of land required by agricultural activity to maintain its ecological functioning or LACAS; Guzmán and González de Molina, 2009), thanks to the synergic interlinkages that can set among funds, the total reproduction costs are not necessarily a cumulative sum (Lemaire and Franzluebbers, 2014; Marull and Tello, 2010).

The generation of internal loops through biomass reuse is highly relevant when we search for the reasons behind this fund-flow synergism that resulted in a significant saving of land. As the amount of available manure was not enough for soil nutrients replenishment, farmers had to rely on burying biomass to keep the reproduction of the soil fund. To cover 36% of the total nitrogen replenishment in this way would entail a highly labour-intensive task. This explains why the maintenance of soil fertility produced a decrease in the overall energy efficiency (FEROI, the amount of energy product per total input), which dropped from 1.18 to 0.43. Likewise, labour energy efficiency (FEROL) decreased from 59.0 to 33.8 MJ produced per MJ of labour performed.

Therefore, we conclude that more intensive land use required a greater flow of biomass reuse (BR), which in turn led to a decrease in energy efficiency. So, land-use intensity also determines what the energy returns may be. This means that taking as a single criterion the final energy efficiency (FEROI), regardless of the reproduction of funds and the LACAS involved in relation to the degree of intensification, would result in what Georgescu-Roegen (1971) criticized as an ‘energetic dogma’. Hence, the high BR and labour costs of land-use intensification have to be taken into account when assessing the energy efficiency of organic agricultural systems.

The MRU land-intensive results, which gave an average of 0.86 ha of surface area required per person, are the most comparable to other previous Chayanovian reproductive studies performed in Catalonia for the same period. This value is consistent with a rough estimate made only in monetary terms by Garrabou and Tello (2008), according to which 4–5 ha of wheat were necessary to maintain an average family of 4.5 people in the same period and study area. Other studies in other Catalan regions estimated a range from 3 to 5 ha in similar soil, climate and technical conditions (Vicedo et al., 2002; Garrabou et al. 2014). Thus, land distributions of less than 0.86 ha/person would not have allowed internal reproduction of peasant farms, and families would have been compelled either to perform off-farm work to earn money, or to sell their own farm products to pay for the external goods acquired in the markets to fulfil self-reproduction. Indeed, they might also have transferred part of this pressure towards other funds (e.g. through soil nutrient mining), thus hindering the conditions required for sustainable reproduction.

As Chayanov argued, a peasant economy might respond to different criteria other than labour allocation efficiency, crop diversification and risk minimization (Chayanov, [1925]1986). Peasants might also have been interested in minimizing labour, provided that their land endowment would allow this. This is what the Peasant Reproduction Unit (PRU) scenario considers. When comparing the land-intensive MRU scenario with the labour-saving PRU scenario, we found that, in order to achieve the reproduction goals of a peasant family with a lower labour requirement, a PRU strategy required a land surface at its disposal 35% larger. Conversely, energy labour productivity (FEROL) would have increased by 51%, from 33.8 to 51.0 MJ per MJ. These results highlight the existence of a crucial trade-off between labour intensity and land cost (Sahlins, 1971; Gingrich et al., 2018). However, in the PRU case gains in labour productivity would have been higher than land costs. Therefore, the labour-saving PRU strategy would have meant an improvement in population wellbeing in terms of consumption–labour ratios, with only a moderate increase in land available for each peasant unit.

6.2 How land use distribution satisfied different farm goals

SAFRA modelling scenarios, and their biophysical fund-flow patterns, allow a better understanding of how different societal goals would have led to different land-use configurations. However, in order to check to what extent these results resembled to reality, we compare them with the actual distribution of land. Beyond its usefulness for environmental history analysis, this is also relevant to verify the reliability for the model to perform prognoses at present, and obtain information regarding the agroecological intensification processes currently proposed (FAO, 2013).

We made use of a database constructed by matching the census of 1855 and the land register of 1850, which contains information for 191 domestic units that represented 89% of the agrarian population and 65% of the total surface area of Sentmenat municipality (Marco et al., forthcoming). We sorted them by the average surface/person, and grouped the resulting distribution by deciles (from D1 to D10; figure 4). Then we compared how the actual farm land-use distribution of the 191 domestic units resembled the modelling scenarios by calculating the cumulative sum of the absolute differences between the percentages of each land use (the Euclidean distances). We considered those real farms whose land-use patterns scored more than 30% of the Euclidian distance to the SAFRA-modelled patterns as bearing no resemblance to these alternative scenarios. This allows us to shed light on some of the reproduction conditions required to maintain their own DU, livestock and soil fertility, as well as on the likely farming goals they might have mainly pursued.

Table 4. Resemblance (Euclidean distance <30%) of actual farms with the counterfactual scenarios considered, distributed in deciles by the average surface per person available in each domestic unit. Source: our own.

Decile	MRU	PRU	MSS(1)	MSS(2)	MSS(3)	NONE	Total	Average surface/ person
D1				5	12	2	19	0,17
D2				4	15		19	0,36
D3				3	14	2	19	0,40
D4				5	13	1	19	0,50
D5				5	12	2	19	0,52
D6				6	10	4	20	0,67
D7				3	12	4	19	0,85
D8				5	11	3	19	1,06
D9		1	4	6	5	3	19	2,05
D10	2	7	8	1		1	19	3,39
Total	**2**	**8**	**12**	**43**	**104**	**22**	**191**	**1,32***

* average value of surface/person in the database.

We found that 89% of farms fit with the land-use pattern of the scenarios considered to date (assuming Euclidian distances lower than 30%; Table 4). It is clear from these results that the actual land distribution did not respond to the basic needs of peasants' self-sufficiency through land-saving (MRU), as only two farms in the whole municipality fit more with MRU than any other scenario. More than 60% of land distributions from deciles D1 to D8 actually resembled the specialization process of the Maximum Sustainable Specialization, specifically to MSS(3). In D9 we found that most of the farms were more similar to the commercial MSS(2) strategy, but also to the commercial MSS(3) and MSS(1), which allowed the external labour and food supplies to be increased, while for D10 the main similarity was the limited vineyard specialization MSS(1) and the labour-saving PRU. Therefore, among D9 and D10 76% of farms were approaching an autonomous reproductive strategy through either vineyard specialization MSS(1) and MSS(2), or by following the labour-saving PRU strategy (only two of them fitted the land-saving MRU case), which is consistent with the fact that they had enough land to do so and they opted for less intensive land uses in order to spare labour hired and reduce their dependence on markets for firewood provision and animal feeding (Marco et al., forthcoming; Garrabou, Cussó & Tello, 2007).

In farms up to the D8 percentile, there was not enough land per person to follow autonomous reproductive strategies at the farm level without heavily relying on the labour and goods markets—a well-known feature sometimes called ‘forced commerce’ (Bhaduri, 1986; Tello, 1990). We calculate that, in order to earn enough money to buy all the goods required to survive (food and wood, housing and clothes), and to pay taxes, around 0.56–0.63 ha/person would have been required. This level was not reached until D6, meaning that at least 60% of farms would have been forced to sell labour to earn enough money for survival. Previous work using other approaches showed a slightly higher percentage at around 73% (Marco et al., forthcoming).

Various agroecological problems were identified in our analysis. In Tello et al. (2012) and Galán del Castillo (2012) the nutrient analysis done at the same municipal level showed a lack of nitrogen replenishment in mid-nineteenth century. When analysing the flow of soil nutrients at the farm level we noticed that these local problems could be concentrated in particular social strata. As seen in Table 3, in all the commercial MSS scenarios burying biomass was the most important strategy to close nutrient cycles. An important share of this biomass came from forests as green shoots and litter. However, below D9 the share in the forest was insufficient to ensure this type of nutrient replenishment, which probably meant that many of these farms were mining soil nutrients. Those smallholders without sufficient access to woodland had to rely on their own vine pruning, and faced the dilemma of either using them for heating and cooking at home or fertilizing their vineyards. This in turn was validated by sources regarding prosecutions due to plundering in the large landowners’ forests (Roca, 1997), and helps explain the use of highly labour-intensive practices in vineyards such as burning the so-called ‘*formiguers*’ due to the scarcity of other fertilizing sources (Garrabou and Planas, 1998; Olarieta et al., 2011).

Finally, by comparing D9 and D10 with the limited commercial MSS(1) and the land-saving MRU strategy it becomes apparent that such farms had a surplus in terms of food, mainly cereals, which means that local food security with respect to basic grains was mainly in the hands of the richest landowners.

7. Conclusions

In this paper we lay the foundations of a Sustainable Agroecological Farm Reproductive Analysis (SAFRA) through socio-metabolic optimization modelling of the different flows that interlinked three live funds for agroecosystem sustainability in a historical case study: the peasant family unit, the livestock, and farmland. Our SAFRA model relies on the approaches put forward by Alexander V. Chayanov ([1925]1985; Van der Ploeg, 2014) and food systems analysis, and goes beyond them by adopting a socio-metabolic perspective from a fund-flow analytical standpoint. It can be used for counterfactual historical analysis, as in the example provided here, although it is mainly aimed at generating scenarios for more sustainable farm systems based on the biophysical limits and capacities of agroecosystem functioning at present.

Regarding the limitations of the model, in this initial version we only assessed three main funds of the agroecosystem, putting aside the farmland-associated biodiversity that we intend to assess in further research by including the links between social metabolism and landscape ecology (Marull et al., 2018). We consider this a first step towards linking Social Metabolism with Environmental History through quantitative counterfactual analysis. The degree of resemblance of the SAFRA-modelled counterfactuals obtained in the initial test of this article with the actual land distributions in the example used hints at the robustness of the model. However, the model only considers static yields, and could lead to underestimates in years with extreme weather or crop failures. Moreover, the main forthcoming challenge will lie in using improved versions to develop prospective scenarios to help deliberative processes on how agroecological funds could be managed to achieve sustainable agroecosystems in the future.

For the first time, the results of this study have quantitatively assessed the synergies that can take place among land uses and land–livestock relationships to reduce land requirements when funds are closely integrated. Agroecosystem funds have a dual role, as suppliers and consumers of biophysical flows. By linking the product and by-product flows of one fund to another, the amount of land required to meet their reproductive needs could be substantially reduced. This is relevant when assessing the Land Cost of Sustainability or LACAS (Guzmán and González de Molina, 2009), and the Energy Returns on Inputs of agroecosystems (Tello et al., 2016; Galán et al. 2016). This raises concerns regarding the competition among land uses devoted to feeding animals or to providing food for humans (Haberl, 2015). We consider that our SAFRA model could help to better understand the key drivers at stake, and to plan more sustainable farm systems.

As an applied history research, the results show how by integrating the management of farmland and livestock, which nowadays would be associated with eco-functional intensification practices (FAO, 2013), was a relevant strategy to achieve sustainable farm systems in the context of increasing population densities under past organic conditions despite the greater effort in terms of human labour they required. This is also relevant for advancing organic farming towards more agroecological landscapes and territories (Wezel et al. 2016). These findings highlight the relevant role that forests and pastures can play as soil nutrient suppliers, when they are agroecologically integrated with cropland through a complex multipurpose livestock feeding strategy (Krausmann, 2004). They show the importance of retaining complex crop rotations and multi-crop associations, as farmers did in past organic agricultural systems, which created agroecologically functional landscape mosaics (Cattaneo et al., 2019; Marull et al., 2008; Tello and González de Molina, 2017). They also make apparent the greater labour efficiency obtained by following an extensive strategy instead of only promoting a higher rural population density when searching for more equitable land distributions. Last but not least, they show that a certain degree of cash-crop specialization can be implemented while maintaining relevant levels of local food sovereignty in a sustainable manner, but only as long as some key biophysical cycles can be closed within a functional agroecological territory (Wezel et al., 2016; Marull et al., 2016; Tello and González de Molina, 2017).

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SUPPLEMENTARY MATERIAL: THE LINEAR OPTIMIZATION PROGRAMME[4]

We present below the data and assumptions of the linear optimization programme used. To this end, we draw on the main variables that define the size of the farm. Then we explain the assumptions and boundary conditions of the three funds considered: Domestic Unit (DU), livestock and farmland. Subsequently, we specify the constraints given by biophysical conditions as well as cultural factors, presenting them according to the fund they correspond to.

The time frame considered to run the programme is a whole year. This does not contradict a dynamic view of the agroecosystem functioning. Farmers' decisions are ever changing over time, and so do the natural processes they are coproducing with. Hence, flow interactions among these funds will be different from one year to another. The data taken to specify the variables, parameters and constrains of the linear programming model are average values that usually averaged the oscillations of the last five years. Yet, in order to ensure sustainability for the years to come the needs of these funds had to be met within those average values of the annual flows considered.

1. Funds and boundary conditions

Once the main variables are defined, we have to characterize the dimension of the soil fund (in terms of surface area) by setting the assumptions and boundary conditions that affect the size of the three main funds of an agroecosystem: Domestic Unit, livestock and non-domesticated species. We consider boundary conditions to be the dimension of DU and livestock, while the optimization will be regarding the total surface of farmland. This is reasonable for the domestic unit (DU), as its composition was a socio-cultural condition, but not for livestock density[5]. Therefore, we will have to double check whether in an optimized scenario it would be better to increase or decrease the livestock component. In further methodological developments, this issue will be solved using non-linear optimization.

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[4] The code is available upon request.

[5] The dimension of the Domestic Unit depended on the available farmland surface, and was also defined by social traditions and conditions. Indeed, if we run the model asking for the minimum surface required to reproduce an agroecosystem, the dimension of Domestic Unit will always be one average person. Conversely, there was no apparent limitation on having more or less livestock in a farm other than the corresponding feed requirement, and our model sets no restrictions on this as long as they were locally bred species.

1.1 Domestic Unit (DU)

From the 1860 municipal population census of Sentmenat we obtain the average domestic structure, counting both family and non-family members (servants), of the 191 farms of which we have specific information on their composition. Average was 5.08 people per DU, median was 5 people, and 4 people the modal. We will take 5 people on average for each Domestic Unit (DU).

Once we analysed the 30 DU with 5 individuals, their modal composition included a girl between 0, a boy from 5 to 10, a man between 18 and 60, a woman between 18 and 60, and a man over 60 years old. This will be our average DU, and its structure affects in our SAFRA model the consumption of food (regarding each type of diet),the work capacity, and the monetary requirements for clothes and shoes (as will be seen later in terms of constraints).

This DU structure fits the Consumers/Workers ratio that existed at municipal level. Yet, in order to avoid an overestimation of farmland capacity, and to extrapolate results at municipal level, we need to verify as well that this composition corresponds to the maximum requirement of surface throughout the family live cycle. Thus, we calculate the Minimum Reproduction Unit (MRU; i.e., the most variable scenario regarding this boundary condition) for the five stages of the family life cycle that we defined in Table 2. The modal composition presented above corresponds to stage 2.

Table 2. Scenarios of evolution of the family structure; *W* indicates woman and *M* man. Data in years

Stage	**1 (*W*)**	**2 (*M*)**	**3 (*W*)**	**4 (*M*)**	**5 (*M*)**
S1	-	-	20	24	-
S2	2	7	30	34	65
S3	12	17	40	44	-
S4	22	-	50	54	-
S5	-	-	60	64	-

Source: Our own, based on the sources detailed in the text.

Once we run the MRU model in these 5 stages, the resulting profile in terms of required land surface is the one indicated in Figure 1. As can be seen, stage 2 was the one that required the greater surface. Therefore, regardless of whether this stage is taken to represent the evolution at municipal level, the result will be suitable for the whole family cycle (that is, a complete generation).

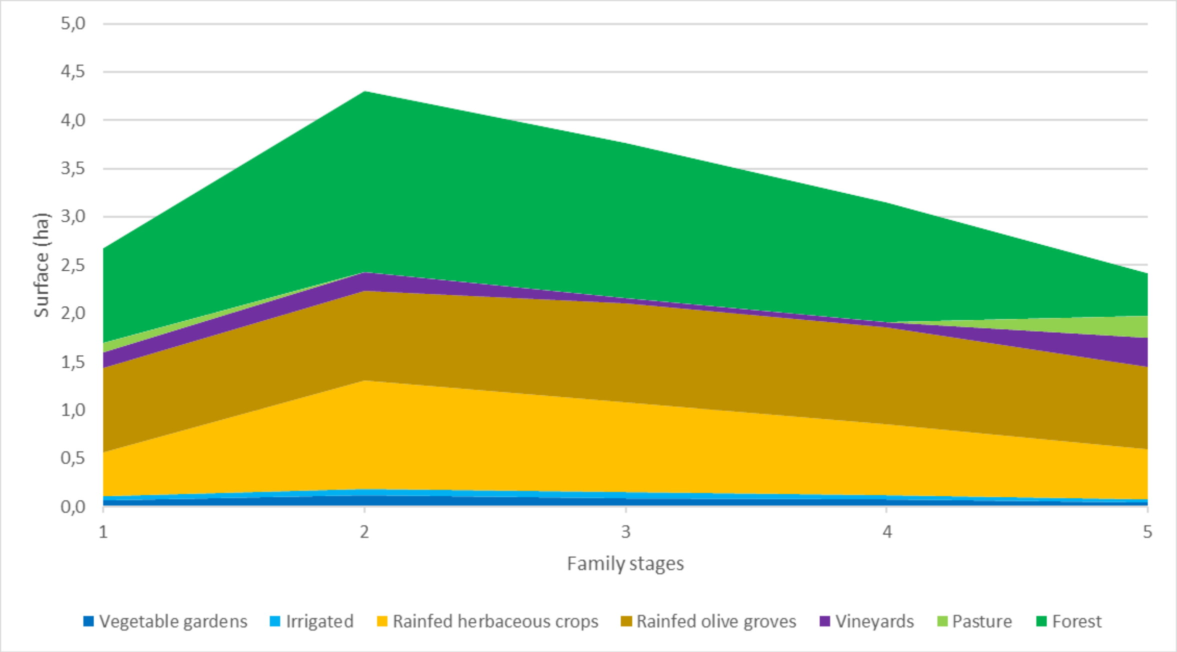

Figure 1. Evolution of the surface required in MRU according to the family live cycle. Source: Our own, based on the sources detailed in the text

In order to be able to extrapolate the results at municipal scale, we have to take into account the different DU compositions within the whole population. Therefore, we weighted the results based on the number of people in the UD. For that purpose, we define the *Z* parameter, which is an integer value according to the number of individuals in the farm. As indicated above, at farm scale analysis we use as a reference *Z*=5. Notwithstanding, when extrapolating the potential development at municipal level results are weighted according to the distribution of frequencies for each composition of DU. Frequency distribution in Sentmenat c.1855 is presented in Figure 2.

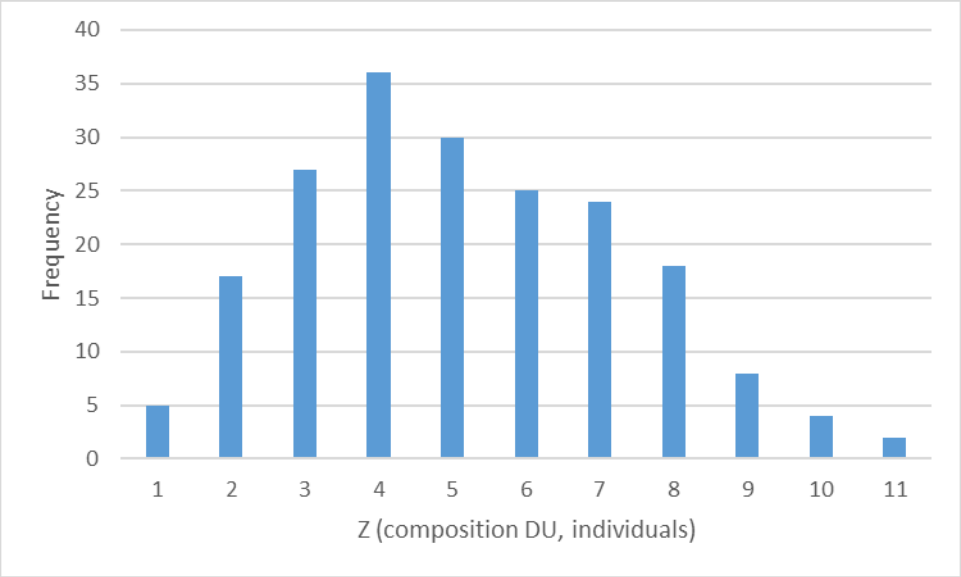

Figure 2. Frequency of DU for each composition

Source: Our own, based on the sources detailed in the text.

1.2 Livestock

As indicated in the article, we distinguish between two types of domestic animals: meat and dairy producing animals, and draught animals. We base their dimension on the other two funds. Meat and dairy producing animals, or consumption animals, depend on the size of the DU (*Z*), while draught animals depend on the amount of land to be ploughed and tilled (cropland area) according to the prevailing farm management in the Vallès County at that time (Roca, 2007).

For consumption animals we consider that a family of 5 people had 1 rabbit, 2 chickens, 2 hens and 1 pig (Marco et al., 2017). We included ovine and caprine heads as well into these consumption animals. At municipal level, according to the livestock census of 1860, there were 2,835 units, which once distributed among DUs represented 1.6 units/DU. We rounded up that value to 2 animals/DU, which would be sheep as it was the most common meat consumed in those rural areas.

For draught animals we consider that smallholder farms shared mules (the predominant ones according to the livestock census of 1860), meaning that their feeding was proportional to the farmland area possessed (Roca, 2007). Since Sentmenat had an standardized weight of draught animals of 115.8 LU500, if we divide this among the 1,757 ha of cropland area we get 0.1011 mules/ha. We define a parameter *M* that indicates the estimated livestock density endowment (in terms of mule sharing; Eq.2). Therefore, we multiply *M* by the total surface of the farm.

$$M = 0.1011\,(X_1 + X_2 + X_3 + X_4 + X_6 + X_8 + X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + X_{17} + X_{18}) \qquad \text{(Eq. 2)}^{6}$$

1.3 Farmland

We assume in our reproductive model that data on productivity provided by sources respond to a static equilibrium. Therefore, as long as farmers ensured nutrients replenishment, land productivity would have kept steady. Land productivity data has been taken from the *Estudio Agrícola del Vallès* of 1874 (Garrabou and Planas, 1998), and the estimates of all its by-products through ratios compiled in Guzmán et al., (2014). Data is about the edible fraction, once the required seed for the coming year was subtracted.

2. Constraints

General constraints fix the relationship between the total area of a land use, and the directions each product or by-product obtained in this use can take. These constraints all take a similar configuration, as indicated in Eq.1 (where X_i is the surface of a specific use (along X_1 and X_{22}), and $X_{i,j,k}$ the share of this surface i, the product *j* of which is going in the direction *j*). The same would happen with $Y_{l,m,n}$

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[6] As can be seen on the total surface area cultivated, neither X_5, X_7 nor X_{18} appear in the formula. The reason is that their areas are accounted in other uses or vice versa, as indicated in section 3.1 of this Supplementary Material.

$$X_i = \sum_{k=1}^{k=n} X_{i,j,k} \text{ where } X_{i,j,k} \geq 0 \text{ (Eq.3)}$$

2.1 Constraints for farmland

We start with the constraints that affect the agrological capacities of the cultivated land at municipal level, taking the site-specific cultural practices into account. For this section, we use the information given in the municipal land-use register (*Amillaramiento*) of 1859 on the extent of each soil quality, as well as the crop rotation systems described in the *Estudio agrícola del Vallés* of 1874 (Garrabou and Planas, 1998).

2.1.1 Distribution of soil quality in the municipality

For land uses that appear in more than one quality, we define general constraints for irrigated wheat (characterized by X_4), dryland wheat (X_8), rye & wheat mixture (X_{11}), potatoes (X_{14}), olive tree groves (X_{18}), vineyards (X_{19}) and forest (X_{22}).

As well, we include specific equations corresponding to the first and second soil quality surfaces, so that their distribution does not overestimate the productive capacity of each type of land unit in the territory. This allows the results obtained as yields per unit of land to be extrapolated at municipal scale

Here it is important to explain a relevant assumption regarding soil quality. We assumed that each soil quality registered by crops is interchangeable to other uses. While this could be true for dryland crops and vines it is less suitable for a change from forest to dryland crop. Indeed, from a historical perspective, land intensification in the area was mainly driven by the emphyteutic *rabassa morta* contracts. There, forest areas where leased to poor farmers who had to clear forest and plant vineyards. Very often those areas where in steep land, and farmers were forced to build terraces so as to protect them from erosion. Fieldwork done in a neighbouring municipality Olarieta et al., (2008) recorded that around 43% of cropped area required *landesque capital* investments in the form of terraces and soil conservation practices. Therefore, the assumption that steep forest areas could be cropped despite their agrological low value seems to be reasonable in a context of those unequal land-use intensification practices. Finally, the results obtained in the extreme value of MSS(3) would have meant changing the use of 416 additional hectares of forest and pastures into vineyards. However, as presented in table 4, c.1860 there were still more than 430 ha below a slope of 30%, and 770 ha below 60%. Therefore, due to this ‘free labour’ that farmers had to invest in constructing terraces, and considering that there was still room for planting more vineyards in areas with less slope, we consider reasonable to validate as technologically feasible the extreme scenario in terms of total cropland area.

Table 4. Distribution of forest in Sentmenat by slope c.1860

Slope (%)	Surface (ha)
0-10	143.6
10-20	145.0
20-30	149.7
30-60	332.0
>60	63.7

Source: Our own, based on the sources detailed in the text.

2.1.2 Total irrigated surface and total farm surface

In order to ensure the adequacy of results to the edaphic capabilities we include two additional boundary conditions. For this purpose we consider that the whole irrigated area that existed, according to the municipal land tax register sources of Sentmenat, was the maximum possible irrigated land under those cultural practices and available technologies. So, the amount of land used with this irrigated crop rotation has to represent in the farm-type considered the same percentage as at the municipal level. With a total surface of 42.54 ha over the 2,781 ha of farmland, that proportion was 1.53%

2.1.3 Crop rotations

The rotation for irrigated lands implied tilling more than a crop a year. Wheat (X_4) was followed after harvested, within the same year, by corn (X_5) sown in half of the land, while the other half was left in fallow (X_{20}). The same happened after hemp (X_6) and beans (X_7) for the second year. Thus, the total irrigated area will be expressed by the sum between X_4 and X_6, amounting X_5, X_7 and X_{20} the same surface as the former. We do not count as total surface the latter, because crop is produced within the same space although at different moments along one year.

In the herbaceous dryland there was also a rotation for each soil quality. In the first one there was a biennial rotation of wheat and beans; in the second one it was of wheat and forage, and in the third of rye & wheat mixture and vetches

The cultivation of olive trees was associated to various grains intercropped in between the rows of trees according to the soil quality. Land productivities of the original historical sources contemplated that farmers cultivated olive trees and other herbaceous crops simultaneously, as an associated silvoarable farming. This means that both perennial and annual crops were grown on the same land at the same time, so total olive groves' rotation area will be either X_{18} or the sum of all the associated crops. .

2.2 Constraints for livestock breeding

Regarding livestock feeding, the model begins from the energy requirements of each type of animal accounted as metabolizable energy (ME). The energy needs of animals are primarily estimated from Church (1984), as well as using other secondary sources (Brenes et al., 1978; Burden, 2012; Giménez, 1994; National Research Council, 1989) from which we estimate the requirements shown in Table 5.

Table 5. Animal energy requirements

	Energy requirements	
	Daily (Kcal/day)	Annuals (MJ/year)
Mules	12,491	19,076
Sheep	1,567	2,393
Hens	356	544
Chickens	269	411
Rabbits	317	317
Pigs	3,900	5,956

Source: Our own, based on the sources detailed in the text.

We therefore identify which resources were suitable for feeding each animal, following the criteria indicated below:

- Straw and stubble: Includes wheat stump, hoof and stubble (from dryland, irrigated, associated to olive tree groves and mixed with rye), and the same with barley. We consider all animals suitable for consuming straw, with the exception of pigs, poultry and rabbits.
- Grain: A part of the main production was destined to animal feeding. Included barley, corn and legumes (dryland and irrigated beans, vetches and lupines). It was suitable for all animals.
- Horticultural by-products: We estimate its composition from a mixture of the leftovers of various vegetables (pumpkin, beans, lettuce, turnips, tomatoes and carrots). They were used to feed pigs, poultry and rabbits.
- Pomace of vine grapes and olives: Farmers also used pomaces for feeding pigs, poultry and rabbits.
- Olive tree browsing: These were the tender shoots of olive trees, which farmers used to feed herds, mainly of pigs.
- Fodder: Draught animals, as well as sheep, complemented their feeding with such kind of production.
- Domestic residues: They were the basis for the feeding of chickens, hens, rabbits and pigs.
- Oak acorns from forest: In the case of pigs, we consider that a relevant part of its feeding came from grazing in oak forests.

- Grazing in pastures and forests: Sheep, but also draught animals, where fed using grazing lands.

In order to know the contribution in terms of metabolizable energy of each possible kind of feed, Table 6 shows its contribution per kg in dry and per animal. When some cells appear empty it means that this was an unsuitable feed, or not commonly used for the specific animals considered.

Table 6. Metabolizable energy values (MJ/kg of dry matter) regarding kinds of feeds and species

		igs	**oultry**	**l** **abbits**	**F** **heep**	**ules**
Straw and stubble	**Cereals**					.72
	Leguminous					.44
Grain	**Barley**	.06	.80	2 .10	3	.30
	Corn	.39	.18	3 .15	3	.46
	Legumes		.60	2 .05	3	.12
Horticultural residues		.05	.51	(.07	1	
Olive oil pomace		.71				
Grapevine pomace		.71				
Olive tree browsing		.48				
Forages		.71			.36	.36
Domestic residues		.25	.00	1 .50	1	
Oak acorns		.08				
Pasture					.15	.46

Source: Our own, based on the sources detailed in the text.

Once the variables are defined in terms of productivities, moisture and energy content of each feed, we proceed to perform the specific constraints of animal feeding for each species. In some cases, we include physiological limitations based on the maximum recommended shares in the diet of certain kinds of products (FEDNA, 2010).

We define several constraints for mules. First, on the one hand, the inclusion of the *M* parameter requires fixing a constraint according to which the pasture consumption is less than the total consumption of feed. On the other hand, fodder cannot account for more than 45% of diet (Eq.53), and cereal straw must reach a maximum of 25%.

Regarding stall bedding, tt is also necessary to consider the amount of crop by-products needed. Using Soroa (1953) as historical source, we assume that mules required 2 kg of stall bedding per day, 0.2 kg/day for sheep, and 1.5 kg/day for pigs and. From UPAE (2011) we assume for poultry and rabbits 1.25 kg/year.

Finally, we use data on the working capacity of draught animal power assuming an average working period of 220 days/year. Sources are the same ones used for labour in section 2.4.3.

2.3 Constraints for maintaining soil chemical fertility

With respect to the flows needed for soil fertility maintenance, we divide the whole cropland surface among 5 different crop systems, mainly based on crop rotations. These were: orchards and fruit trees, irrigated crops, herbaceous dryland crops, associated crops in olive tree groves, and vineyards. We consider three different kinds of cultural practices for fertilization, which were used for one or more of the different crop systems:

- Application of humanure: We consider that its application was limited to vegetable gardens, irrigated crops and herbaceous dryland, which were located on the lands closest to the farmhouse.
- Application of animal manure with its corresponding beds: These were applied in all crops except for vegetable gardens and fruit tree orchards where we assume they were not necessary.
- Burying biomass: It is known that the burial of biomass was a common practice, and it was done both for all dry crops and in vineyards.

We characterize those practices regarding its fertilization potential, in terms of the main macronutrients (nitrogen, phosphorus and potassium) content.

Animal manure comprises two different phases: On the one hand animal excreta, and on the other hand stall beds on which this excreta remains. It is a rather complex issue to decide the composition of animal feeding, given that the actual collection of excreta depended on the number of days animals grazed. We assume that all the flows of feeding were obtained at municipal scale in 1860 (Marco et al., 2017). Thus, we consider the amount of excreta, moisture and grazing days, and its composition in N, P and K in kg of fresh matter taken from the American Society of Agricultural Engineers (ASAE, 2000). Assuming that livestock was 100% of the days of a year grazing, only 45% of excreta could be collected by means of locking the animals in pens at night (Cascón, 1918). Hence, the actual factor of manure application was also determined by considering their grazing period. We show the results in Table 8.

For the case of mules, and given its relevance and multiple possibilities of their feed intake, we generate a *P* parameter in order to define the percentage of manure collected from the total. This *P* depends in turn on a parameter *D*, which is the number of grazing days.

Table 8. Animal excreta composition

Animal	**Excreta**					**Pasture**	
	Production	**Moisture**	**Nitrogen**	**Phosphorus**	**Potassium**	**Days**	**Collected**
	kg/day	**%**		**% fresh matter**			**% total**
Mules	14.64	70.59	0.59	0.14	0.49	*D*	*P*
Sheep	1.20	72.50	1.05	0.22	0.80	365	45.00
Pigs	9.47	86.90	0.62	0.21	0.35	105	84.18
Hens	0.31	75.00	1.31	0.35	0.47	0	100
Chickens	0.23	74.12	1.29	0.35	0.47	0	100
Rabbits	0.18	74.12	1.29	0.35	0.47	0	100

Source: Our own, based on the sources detailed in the text.

To run everything off, we calculate the replenishment requirements for each land use through nutrient balances, mainly following the criteria proposed by González de Molina et al. (2010). The results are presented in Table 10.

Table 10. Requirements in terms of N, P and K (kg/ha) for the different land uses, regarding its soil quality

	Soil Quality	N	P	K
Vegetable gardens		51.00	3.42	11.43
Fresh fruits in orchards		8.35	-2.07	-4.88
Nuts		26.63	0.23	2.97
Irrigated wheat	1	42.43	6.15	15.34
	2	34.25	4.88	11.84
	3	23.35	3.19	7.17
Irrigated corn	1	28.03	4.00	8.95
	2	21.98	3.11	6.83
	3	15.94	2.22	4.71
Irrigated hemp	1	45.84	-0.05	0.70
	2	41.82	-0.28	-0.18
	3	37.80	-0.51	-1.07
Irrigated beans	1	-23.72	5.43	20.38
	2	-21.68	4.01	15.01
	3	-19.65	2.58	9.64
Wheat	1	41.46	6.31	5.30
Beans		-4.60	3.65	1.98
Potatoes		13.41	1.34	-1.58
Wheat	2	30.56	4.61	0.64
Fodder		24.67	4.72	14.91
Potatoes		9.69	0.76	-5.21
Rye & wheat mixture	3	21.51	3.21	-3.27
Vetches		-0.96	2.29	3.16
Associated wheat to olive trees	1	27.45	3.73	11.04
Potatoes		17.76	1.62	10.14
Corn	2	14.88	1.64	3.94
Rye & wheat mixture		21.40	2.79	8.42
Barley	2	18.79	2.10	10.49
Lupines		2.64	4.11	6.14
Olive oil	1	25.43	3.10	-4.39
	2	21.36	2.74	-5.48
	3	17.88	2.44	-6.42
Vineyard	1	13.24	1.12	-1.73
	2	10.51	0.79	-3.29
	3	5.97	0.25	-5.88

Source: Our own, based on the sources detailed in the text.

2.4 Constraints for maintaining the Domestic Unit

2.4.1 Food intake

When accounting for diets we will only consider food agroecosystems provided (that is, we exclude fish). Additionally, as already mentioned above, the model assumes that farmers could be free to obtain a perfect agrosilvopastoral mosaic to attain their self-sufficiency, as a counterfactual scenario to be contrasted with the actual situation in which they depended on exports, imports and the volatility of relative prices.

Indeed, historical sources confirm that most products included in the local diet came from the Vallès County. Peasant diets included mainly cereals, potatoes, legumes, oil and wine, with some products of animal origin (Cussó and Garrabou, 2000). Following the criteria of Marco et al. (2017b) we obtained an estimated average consumption for the average family unit of 5 people. Diet was mainly based on bread consumption, and potatoes to a lesser extent, contributing 70% and 12% respectively to daily intake. We show the results in Table 14.

Table 14. Food intake needs by our DU along a year

	Per DU (kg/day)	**Per year and DU (kg)**	**Per year and person (kg)**	**Total consumption (kg/Z)**
Bread	2.42	88.29	176.58	146.56
Olive oil[7]	0.06	22.9	4.58	12.46
Wine	0.40	146.8	29.37	29.37
Legumes	0.12	43.5	8.70	8.70
Potatoes	1.59	580.2	116.04	116.04
Vegetables	0.86	315.3	63.06	63.06
Fresh fruit	0.14	50.5	10.09	10.09
Nuts	0.07	25.2	5.05	5.05
Meat	0.13	45.7	9.14	9.14

Source: Our own, based on the sources detailed in the text.

Therefore, crop distribution in a self-reproductive farm had to ensure that farmers could meet these nutritional needs. For meat we calculated that with the estimated livestock density our DU obtained the total of 65 kg a year of meat required for an average farm at that time, according to the historical sources available.

2.4.2 Firewood for heating

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[7] The model includes the use of oil for illumination. According to our estimates, based on population data given by Garrabou (1,686 people), we estimated the local oil consumption for food and a total dietary consumption. This was 8,833 litres out of the 23,827 litres of apparent consumption in the municipality. The difference (14,994 litres) is divided between the number of certificates of the same source (347). We obtain an annual consumption of 43.20 litres/DU, that is a daily consumption of 0.118 litres/UD or 0.108 kg/UD we added in the food consumption data in the last column.

It is also necessary to take into account that there were constraints on the provision of firewood and wood. So we obtained the partial constraint to the exosomatic firewood consumption by this rural community based on an estimated consumption of 1.56 kg of wood fuel per inhabitant per day, following the criteria of Marco et al. (2017). In addition, as pointed out by Colomé (2016, personal communication), the consumption of vine pruning was considered anecdotal and could not suppose more than 10% of fuel requirements of the DU.

2.4.3 Labour

In terms of labour, the constraint was that the working capacity of the family did not exceed the labour needs of all the farms in the municipality. To calculate this we took, on the one hand, data on labour requirements for crops, forest and livestock maintenance (Garrabou and Planas, 1998). On the other hand, to calculatr human labour capacity we used a monthly accounting to guarantee that there were no seasonal bottlenecks throughout the year.

a) Monthly labour capacity

We calculated the working capacity in the farm-type considered by estimating the ability of the 5 people taking gender and age into consideration. This implied a total availability of 580 workdays throughout a year. However, we decided to consider the working capacity also based on the variation of hours of sunlight along the year. We calculated total hours of sunlight per day, based on latitude data and solar radiation functions, as can be seen in Table 15.

Table 15. Weighting factors concerning total hours of sunlight

	Daily hours of sunlight	**Factor**	**Available workdays (*Z*)**
January	9.37	0.78	7.55
February	10.39	0.87	8.37
March	11.73	0.98	9.45
April	13.15	1.10	10.60
May	14.36	1.20	11.57
June	14.96	1.25	12.05
July	14.67	1.22	11.82
August	13.61	1.13	10.96
September	12.23	1.02	9.85
October	10.80	0.90	8.70
November	9.61	0.80	7.74
December	9.03	0.75	7.28
	12.00	1.00	9.66

Source: Our own, based on the sources detailed in the text.

b) *Monthly requirements by crop*

We calculated requirements for each crop on a monthly basis by weighting the annual data given in *Amillaramientos del Vallès* with the monthly distribution patterns detailed in Garrabou et al. (1992). The available data contains monthly workdays per hectare for the Counties of Empordà (1850-1870, 1930-1936), La Segarra (1880-1890), Vic (1830-1840, 1880-1890, 1930-1950) and El Penedès (1903-1907), all of them in Catalonia. We present this data in Table 16.

Table 16. Monthly requirements in workdays/ha

	Month												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
Vegetable gardens	6.1	6 1	8 5	13.6	15.3	15.3	18.8	18.8	17.0	10.0	6 8	6.1	142.4
Fresh fruits	0.0	3 3	0 0	0.0	0.0	1.9	1.9	5.3	5.3	0.0	0 0	0.0	17.7
Nuts	0.0	3 3	0 0	0.0	0.0	1.9	1.9	5.3	5.3	0.0	0 0	0.0	17.7
Wheat	0.0	4 9	8 7	2.4	0.0	4.8	14.1	3.9	1.9	5.3	3 4	0.0	49.5
Corn	0.0	4 2	7 3	1.0	9.1	7.2	0.0	4.4	1.9	8.3	0 0	8.7	52.0
Hemp	18.2	0 0	26 1	5,3	3.3	3.3	3.3	3.3	14.4	13.8	40 1	62.6	193.7
Beans	9.2	9 1	0 0	9.1	0.0	10.6	4.8	0.0	12.8	0.0	8 0	1.5	65.1
Wheat	0.0	4 9	8 8	2.5	0.0	4.8	14.2	3.9	2.0	5.4	3 4	0.0	50.0
Associated wheat	0.0	5 0	9 0	2.5	0.0	4.9	14.5	4.0	2.0	5.5	3 5	0.0	51.0
Corn	0.0	4 2	7 3	1.0	9.1	7.2	0.0	4.4	1.9	8.4	0 0	8.8	52.3
Rye & wheat mixture	0.0	6 2	9 7	4.2	0.0	4.2	9.6	3.4	2.9	4.7	3 5	0.0	48.3
Barley	0.0	2 1	4 2	2.1	0.0	4.7	14.3	14.7	3.0	2.5	0 4	0.0	48.1
Fodder	5.2	5 2	5 7	0.0	8.6	4.4	7.4	5.9	3.9	3.9	0 0	0.0	50.2
Potatoes	0.0	0 0	14 9	0.0	6.4	6.4	0.0	0.0	35.5	10.6	5 2	0.0	79.0
Beans	9.2	9 1	0 0	9.1	0.0	10.6	4.8	0.0	12.8	0.0	8 0	1.5	65.1
Vetches	9.2	9 1	0 0	9.1	0.0	10.6	4.8	0.0	12.8	0.0	8 0	1.5	65.1
Lupines	9.2	9 1	0 0	9.1	0.0	10.6	4.8	0.0	12.8	0.0	8 0	1.5	65.1
Olive trees	6.8	0 0	14 9	14.9	12.2	5.4	0.0	0.0	0.0	0.0	0 0	27.1	81.2
Vineyards	0.0	0 0	5 1	13.1	4.7	5.0	0.6	0.0	1.8	12.0	1 1	0.0	43.4

Source: Our own, based on the sources detailed in the text.

Regarding the care of livestock, there is a minimum of 35.5 workdays/year per mule and 27.87 workdays/year for the rest of livestock for a Z=5.

We add to these labour requirements the ones required by cropland fertilization, according to each type of fertilizing management, and using estimates from Soroa (1953). However, not all fertilization tasks took place in the same months. Thus, they are distributed based on cultivation schedules defined in Garrabou et al. (2012).

2.4.4 Monetary requirements

As a source to establish other economic necessities of our DU, we mainly used a study carried out on reproduction expenses of a rural DU in Catalonia in a context of wine-growing specialization (Colomé, 2015). For clothing and footwear Colomé proposes an average annual cost for an adult man of about 30 *pesetas*. Using the proposed factors on age for the whole family, this implies a total of 109.2 *pesetas* per DU, or 21.84**Z* *pesetas*. For housing expenses, in order to pay the annual rent a peasant family would need the equivalent of about 36 workdays in the Catalan Penedès County in 1872. We considered that the average agricultural wage was around 72 *pesetas* (Colomé, 1996). However, at Catalan level another average has been set at around 85 *pesetas* (Vicedo et al., 2002). Summing up, expenses associated with the maintenance of the DU will be 21.84**Z* + 85 pesetas. Also as part of the maintenance of the DU we considered the cost of keeping and replacing the equipment of farm implements in order to use them in a sustainable manner. In this case, a study also cited by Colomé (1996) fixed the cost of amortization of farm implements in the municipality of Santa Margarida i els Monjos (Alt Penedès County) at 2.04 *pesetas*/ha, a value that we will be taken as a reference in our case. The annual cost of maintenance of the barrel and cellar for wine producing is estimated at 19.9 *pesetas*, according to Colomé (1996).

With regard to tax burdens, we consider the costs of paying the royal land, housing and livestock cadastral taxes, and the municipal ones. Regarding the seigneurial censuses paid to the Marquis de Sentmenat, although it is true that some of them continued to be paid even at that time or even later, due to their devaluation through price inflation we considered them to be anecdotal. According to the *Distribution of Personal Wealth in Real Estate Ownership of 1852 in the Barcelona Province* (Library of the University of Barcelona, reference 146-1-II/13), in Sentmenat the cadastral taxes paid ranged on average 15% of taxable liquid incomes estimated (with a R^2 of 0.9996). The municipal taxes were accounted as a surcharge on this royal one, in such a way that surely ended up representing a direct tax burden of 20% of agricultural incomes calculated through the taxable liquid values set in the cadastre.

So as to identify the relationship set between the types and qualities of land and the tax burden paid, we made a multiple regression analysis relating the crop surface data of the 1859 municipal land register (*Amillaramiento*) and the taxable liquid incomes determined by the cadastre. The correlation had a R^2 value of 0.745.

Likewise, we carried out a regression analysis on the valuation of the taxable liquid according to livestock owned. We get that a mule was computed as 34 *reales* of additional taxable income, a pig as 7.9, and a sheep as 1.3 (after 1869, 1 Spanish *peseta* = 4 *reales*).

Once the most basic monetary needs are satisfied, we calculated the total contribution of the farm surplus in monetary terms. For this, we estimated the potential sources of money that came from each crop. Given the approximate value of this constraint, we decided only to contemplate the surplus of the main products, and not what could be obtained from the sale of minor items such as straw (which had a small value). We obtained prices mainly from the *Estudio Agrícola del Vallés* of 1874.

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