Sociometabolic analysis of a traditional Mediterranean agroecosystem

Historical transition and Biocultural Heritage.
(Les Oluges, Catalonia, c.1860-1959-1999)

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PhD in Economic History

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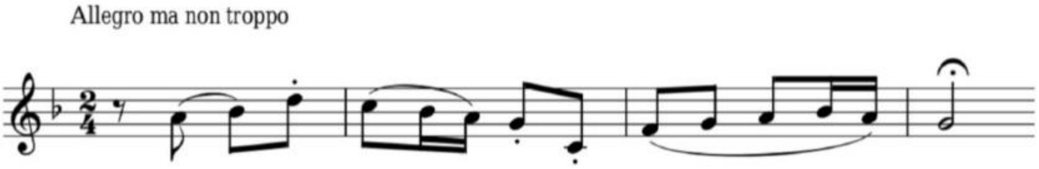
Beethoven, *Symphony no. 6 Op. 68, (Pastorale). ‘‘Awakening of cheerful feelings on arrival in the countryside’’*

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Pero por supuesto, otra parte fundamental del ecosistema social que me ha sostenido durante estos años han sido mi familia y amigxs. Mi llegada a Barcelona fue hermosa gracias a Bernat y su piano. Poco a poco mi red en Barcelona ha ido creciendo, y uno de sus nodos principales ha sido sin duda Albert, compañero de vida y de sueños, que me ha cuidado con todo su corazón cuando lo he necesitado y me ha invitado siempre a escapar, a bailar y a reír. Él, sus padres y sus amigos han sido una ayuda importante para recargar pilas entre tanta tesis. Pero más allá de Barcelona, los apoyos han venido desde muchos lugares y muchos tiempos. Amigxs de toda la vida, Gema, Sesi, Mer, Ana, Ville…, que están ahí a pesar de la distancia, ya sea en los reencuentros, en los teléfonos o incluso por carta. Amigxs que aparecieron en algún punto, Sigrun, Alba, Javi, Rubén, Natalia, Héctor… y que siguen (¡y que sigan!) apareciendo y reapareciendo para compartir experiencias y abrazos. Y como no, mi familia, cuyos lazos son siempre abrigo y soporte. En especial, quiero darle las gracias a Mamen, por su fuerza y su aliento que me hace grande y a mis padres, que son brazos abiertos, mano tendida y sonrisa dispuesta, no hay gracias en las que quepa todo lo que les agradezco.

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1Q	First quality soil
2Q	Second quality soil
3Q	Third quality soil
AFEROI	Agroecological Final Energy Return On Investment
AWU	Annual Working Units
B	Barley
B&O	Barley and Olive trees
B&V	Barley and Vines
BR	Biomass Reused
BV&O	Barley, Vines and Olive trees
CAP	European Common Agricultural Policy
EFEROI	External Final Energy Return On Investment
EI	External Inputs
EROI	Energy Return On Investment
FAO	Food and Agriculture Organization of the United Nations
FEROI	Final Energy Return on Investment
FP	Final Produce
GCV	Gross Calorific Value
GDP	Gross Domestic Product
HANPP	Human Appropriation of Net Primary Productivity
IFEROI	Internal Final Energy Return on Investment
LACAS	Land Cost of Agrarian Sustainability
LER	Land Equivalent Ratio
LU500	Livestock Units of a standardised weight of 500 kg
$\mathbf{NPP_{act}}$	Actual Net Primary Productivity
O	Olive trees
R	Rye
R&O	Rye and Olive trees
RV&O	Rye, Vines and Olive trees
SFS	Sustainable Farm Systems research group
TIC	Total Inputs Consumed
TP	Total Produce

UhP	Unharvested Phytomass
V	Vines
V&O	Vines and Olive trees
W (Chapter 2)	Waste
W (Chapter 4)	Wheat
W&O	Wheat and Olive trees
W&V	Wheat and Vines
WV&O	Wheat, Vines and Olive trees

Publications derived from this thesis

Two chapters of this PhD thesis have been originally published or submitted in the following journals and international publishing companies included in the Web of Science:

- Lucía Díez, Xavier Cussó, Roc Padró, Inés Marco, Claudio Cattaneo, José Ramón Olarieta, Ramón Garrabou & Enric Tello (2018): "More than energy transformations: a historical transition from organic to industrialized farm systems in a Mediterranean village (Les Oluges, Catalonia, 1860–1959–1999)", *International Journal of Agricultural Sustainability*, 16:4-5, 399-417, {https://doi.org/10.1080/14735903.2018.1520382} [JCR IF: 2.702; Q1 in Agriculture, Multidisciplinary]

- Lucía Díez Sanjuán, José Ramón Olarieta & Enric Tello (under review): "Below- and aboveground sustainability: Historical management change in a Mediterranean agroecosystem (Les Oluges, Spain, 1860-1959-1999)", *Human Ecology*.

With the red hair of one she-urchin in the gutter I will set fire to all modern civilization. Because a girl should have long hair, she should have clean hair; because she should have clean hair, she should not have an unclean home; because she should not have an unclean home, she should have a free and leisured mother; because she should have a free mother, she should not have an usurious landlord; because there should not be an usurious landlord, there should be redistribution of property; because there should be a redistribution of property, there shall be a revolution. That little urchin with the gold-red hair, whom I have just watched toddling past my house, she shall not be lopped and lamed and altered; her hair shall not be cut short like a convict's; no, all the kingdoms of the earth shall be hacked and mutilated to suit her. She is the human and sacred image; all around her the social fabric shall sway and split and fall; the pillars of society shall be shaken, and the roofs of ages come rushing down, and not one hair of her head shall be harmed.

G. K. Chesterton, *What's wrong with the world*

In truth, it is only by eternal institutions like hair, that we can test passing institutions like empires. If a house is so built as to knock a man's head off when he enters it, it is built wrong.

G. K. Chesterton, *What's wrong with the world*

Introduction

1. *The personal roots of this thesis*

There is an exercise of scientific honesty with which I would like to start. I believe that, especially in social sciences, our scientific approach towards the real world, what we see and how we see it, is determined by who we are, our social position, our values and prejudices, our worldview. There is a subtle degree of subjectivity that is unavoidable, and the only way to approach to it objectively, is by stating it explicitly from the very beginning. Thus, I will start this introduction with a brief presentation of the personal roots of this thesis.

I had my first Economics class in high school. The first day, our teacher told us that Economics was the science that deals with the problem of how to satisfy unlimited human needs with limited resources. That first day I decided that I should study economics, because apparently it was an area with great influence in everyone's life, and looked like something was wrong with it if in its very definition it was confusing needs and desires. Luckily, I had also an amazing Philosophy teacher in high school, with whom I learned the amusement of philosophical reflection. Thus, after high school I ended up studying Economics and Philosophy at the university, because if I was to become economist, I would be one with a sound consideration of what is and what should be. I would like to think that this thesis would not disappoint that 16-year-old girl committed to build a better world.

During the years at the Complutense University in Madrid, I lived and learned between two worlds, feeling sometimes too economist for being a philosopher, sometimes too philosopher for being an economist. However, I found my place in that field of knowledge that is the in-between, in the space in which life, reality, the world, is complex and not easy to grasp; a space with no clear boundaries; a territory with not many, if any, clear, eternal, universal certainties; a realm that moves, changes and transforms, that is flexible and requires flexibility. Through those university years I learned some things, unlearned some others, and built up my epistemological ethos.

When I decided to do a PhD I did it with the conviction that the house we live in (Capitalism) is built wrong, and even though there are different means that could test it (such as feminism, racism and inequality), sustainability was my *red hair* (Chesterton, 1912). My ethical commitment with sustainability is not based only on a concern for social justice, or on a speciesist and anthropocentric interest on trying to guarantee our own survival as species in the current ecological crisis. I consider, of course, the importance of those issues, but I am also convinced that there is an intrinsic value in nature and that every living species has a right to live that ought to be respected (Katie, 2007; Routley, 1973). Additionally, I wanted to focus on agriculture because I understood that the basis of human subsistence is how we obtain our food. No other economic activity makes sense if we are not able to feed ourselves. That was my initial research interest, the starting point from where this work has been built. However, throughout the intellectual journey of this PhD, the research subject has expanded. The two-dimensional geometric form conformed by sustainability and agriculture, now has transformed and acquired the shape of a network of interrelated ideas, facts, theories and concepts. The topic of agricultural sustainability has gained complexity and depth. On the one hand, the investigation process has transformed my initial concept of sustainability. Naïvely understood at the beginning as an ideal state to be achieved, now I use this concept understanding it as a process, a dynamic equilibrium that requires continuous adaptation and decision-making. On the other hand, agriculture has become much more than just growing food: it is a way of living, a cultural expression, an economic activity, a social practice and a way of relating with Nature. This dynamic and complex perspective is somehow a worldview that is not restricted to the field of agricultural sustainability, but can be applied also to social and economic systems as a whole.

When Economy is defined as a life process (Sahlins, 1988) in which markets, money, and profits are just a part but do not constitute the whole, it becomes easier to distinguish the *eternal institutions* from the *passing* ones. Furthermore, it becomes easier to imagine new possibilities. For building a new house, the old one needs to be tested from its foundations. However, building a new house of this kind is an exciting and exhausting task that can only be done collectively. I am glad that throughout these years of PhD I have found many inspiring authors that I have read with delight. And of course, I am very grateful that the University of Barcelona gave me the opportunity to work with a fascinating group of researchers that have not only bright brains but also wonderful hearts.

2. The importance of agriculture and its historical (and future) transformations

Agriculture is a minor economic activity in GDP terms. According to the data available for 2016 from FAO[1] the value added of agriculture as a share of the world GDP was only 4.18%. However, that small proportion of GDP is potentially able to feed the actual world population of more than 7.5 billion people —even though an 11% prevalence of undernourishment exists nowadays due to poverty, food waste and food distribution patterns (Berners-Lee, Kennelly, Watson, & Hewitt, 2018). Additionally, it employs more than one quarter of the labourers worldwide and covers 37% of the total land area. Thus, despite the reduced significance of agriculture in monetary terms, in real terms agriculture is still a major economic activity.

The current global agricultural and food production system has important flaws that can be grouped in two different dimensions. On one hand, there are problems of economic and social inequality caused to a large extent because of the increased presence and power of large global corporations in the industrial agrifood system (Etxezarreta, 2006; McMichael, 2013; Patel, 2012a). On the other hand, modern industrial agriculture is also of great importance in the sustainability crisis that characterises the Capitalocene (Moore, 2017, 2018). This PhD thesis is focused on the second type of problems derived from modern industrial agriculture, but it is important to acknowledge that the social and ecological problematics are ultimately related since they both respond to a structural organization of agricultural production centred on profit maximization.

Agriculture has a key role in global environmental change (Campbell et al., 2017; IPCC, 2014; Tilman, Fargione, et al., 2001). According to the framework of the planetary boundaries proposed by Rockstrom et al. (2009) and Steffen et al. (2015) that establishes the limits that should not be surpassed if we want to avoid an abrupt global environmental change, agriculture has been a major driver in the transgression of two of these boundaries: biogeochemical flows (i.e. the alteration of Nitrogen and Phosphorus global

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[1] http://faostat.fao.org/static/syb/syb_5000.pdf

cycles) and biosphere integrity (i.e. the loss of genetic diversity and functional diversity). Additionally, agriculture is a major driver in two boundaries under increasing risk: freshwater use and land-system change; and a significant driver of a third one: climate change. Together with other human activities, agriculture is pushing these environmental limits risking to destabilize the Earth System with hazardous consequences. Agricultural systems need to be transformed so that their ecological impacts are reduced and mitigated, but agriculture also needs to adapt to the new coming environmental conditions while feeding a larger global population. Transforming agriculture towards a sustainability path is urgent and the changes needed are profound.

These current sustainability problems are not inherent to any agricultural system, rather they are closely related to the modern expansion of a particular agricultural model. During the 20th century, and especially after the Second World War with the spread of the Green Revolution, agriculture experienced a great transformation. Modern industrialized farm systems have achieved a great increase of agricultural output, but at the abovementioned sustainability costs. The differences between traditional and industrial farm systems are sharp (Table 1) since these two agricultural models reflect different technological capacities and contrasting ways of understanding agricultural production and relating with Nature.

Table 1. Main characteristics of traditional and industrialised agricultural systems. Source: own elaboration from (Altieri, 2004; Altieri & Nicholls, 2005; Mazoyer & Roudart, 2006)

Traditional agriculture	**Industrialized agriculture**
-Local resources (environment, knowledge, seeds)	-External resources (standardized technology, knowledge, seeds)
-Organic matter recycling	-Industrial fertilizers
-Polycultures	-Monocultures
-Structural diversity	-Industrial pesticides
-Integrated livestock management	-Industrial livestock management
-Human and animal workforce	-Mechanization
-Medium/small scale	-Large scale

-Self-sufficiency, reduced external/market dependency, functional diversity	-Dependence on external inputs, market orientation, specialization
-Moderate yields	-High yields
-Resilience	-Unsustainability

Understanding how the transition from organic traditional farm systems to industrialized agricultural systems took place and transformed the biophysical, social and economic structure of agroecosystems is important in order to build more sustainable food systems. Traditional farm systems are an important source of ecological knowledge and have certain features (such as the reduced use of external inputs or the resilience capacity) that will be important for building more sustainable farm systems in the future. Analysing which were the drivers of the transition towards industrialized farming, and which were the techniques and strategies that allowed the maintenance of the productive capacity of agroecosystems in the past, is important for the future. Thus, this thesis looks at history in order to learn for the future.

3. *Les Oluges: small is relevant*

Initially, the case study of Les Oluges was conceived to be an introductory exercise in my thesis. The study of a small village in Catalonia for which good historical sources were already available would let me familiarise with the innovative methodology developed by the Sustainable Farm Systems (SFS) international research group before jumping to another case study which could fit more with my initial interests. However, once I stepped into that municipality of La Segarra I had never heard about before, I never left. I stayed in Les Oluges for two reasons. On the one hand there was a pragmatic point: after all the time and effort put on organizing the database and obtaining the first results, it was not clear whether the timespan of my PhD would be compatible with the investment of time needed to clear up a new territory, finding the historical sources needed, building the database and disentangling its functioning. Thus, it made sense trying to make the best use of the database already developed for Les Oluges instead of building a new one. On the other hand, however, there was another cause: from that first analysis there appeared interesting results and some further questions that required a deeper analysis. The more acquainted I got with the particularities of Les Oluges, the more interested I became in understanding it, in analysing its details, in answering the questions that its investigation was rising. Indeed, the research issues stirred by this apparently small case study are not exhausted yet.

The interest on the analysis of Les Oluges was first considered as a contrasting point with the case of study of the Vallès agroecosystem that other colleagues of the SFS Catalan Team were working on. Comparing the transformation paths that agroecosystems pertaining to each of the *two Catalonias* (Vallès as part of the rich, wet, closer to the coast of Catalonia, and Oluges as part of the poor, dry, inner part of Catalonia) (Vilá Valentí & Vila, 1973) was a relevant contribution to the work developed by the SFS research group. However, Les Oluges has ended up earning its own significance as a relevant case study by itself.

The historical evolution of Les Oluges is representative of the changes experienced in the rain-fed cereal-growing agroecosystems of Spain (Mata Olmo, 2002). These agroecosystems were traditionally characterised by relatively tough environmental conditions for agriculture, poor and irregular harvests, highly fragmented cropland, terraced lands and extensive cultivation with fallow every other year, and the predominance of mules and donkeys as draft force. Until the end of the decade of 1950s the use of mineral fertilizers and mechanization were low, but they expanded from the decade of the 1960s transforming profoundly these agroecosystems. A very important rural exodus accompanied this agricultural transformation. Additionally, fallow was reduced and eventually eliminated, cropland expanded, land property increased, and livestock density rose, mainly focused on milk and meat production in intensive stabling and linked to the vertical integration in industrial agrifood chains. These are the basic characteristics of Les Oluges, and of the agroecosystems with largest area in the territory of Spain. Therefore, the historical analysis of Les Oluges is an approach to the changes experienced in great part of the Spanish agroecosystems.

Furthermore, the historical sources of Les Oluges provided the possibility of analysing a particular traditional Mediterranean crop system in great detail. This analysis has been relevant for several reasons. Firstly, because it sheds light into an agricultural practice – the intercropping of cereals with woody crops such as vines, olives and almonds– of which records are scarce but that was widespread in traditional Mediterranean agroecosystems. Secondly, because it challenges one of the key ideas of the modern agricultural model: that competence among crops reduces the productivity in polycultures. Finally, the biocultural analysis of the traditional intercropping system in Les Oluges provides valuable knowledge about the multifunctionality and complexity of sustainable agricultural systems. The study of the silvoarable system in Les Oluges, which is presented in Chapter 4 of this thesis, is a contribution that opens a long path of future research.

Thus, the relevance of the study of this small village from La Segarra is multiple and ample. It was relevant for the work developed in the SFS international research group; for understanding the historical transformation of agricultural systems in great part of Spain, and for improving the understanding and enhancing the importance of a traditional agricultural knowledge that is currently disappearing. In that sense, this PhD thesis seeks to contribute to the international FAO's call to study and value the Globally Important Agricultural Heritage Systems (GIAHS[2]) as important reservoirs of site-specific know-how accumulated over generations that become increasingly important to cope with the Global Change underway. Whether Les Oluges is a globally important case study is an open question, but in any case the methods used to study this small Catalan village and the results obtained are useful to that aim.

4. *Aim and structure of the thesis*

The research on the agroecosystem of Les Oluges started from the recognition that modern industrialized agricultural systems are not sustainable, and was based on the hypothesis that analysing the historical transition from organic to industrialized agricultural systems by means of the Green Revolution, and how it changed the characteristics and functioning on agroecosystems, it is possible to obtain valuable information that can be helpful for the improvement of agricultural sustainability in the future. Thus, this investigation aims to give answer to the following questions: *i*) how did the transition from a traditional organic agroecosystem to an industrial farm system take place?, *ii*) how did this agricultural transformation affect the sustainability of the agroecosystem?, *iii*) which are the main drivers of the unsustainability of modern

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[2] See http://www.fao.org/giahs/background/en/

industrialized agriculture?, and *iv*) what can we learn from traditional agroecosystems in order to build more sustainable farm systems in the future?

The structure of this thesis reflects the intellectual journey that this investigation has entailed. As a map that guides the lines of thought that sustain the thesis, Chapter 1 introduces the theoretical foundations of the research. Then, Chapters 2 to 4 present the corresponding articles that conform the analysis of Les Oluges. From these, the first two chapters focus on the sustainability of the functioning of the agroecosystem from a biophysical perspective in the three points of time studied: *i*) c. 1860, when Les Oluges was a traditional organic farm system; *ii*) 1959, when the agroecosystem operated under a mixed of organic and industrialized functioning; and *iii*) 1999, when Les Oluges was a fully industrialized agroecosystem. Chapter 2 contains the analysis of the historical agricultural transformation of Les Oluges from the perspective of its energy efficiency, while Chapter 3 analyses that historical transformation from belowground, with the nutrient balances of the agroecosystem at the municipal and crop system scales. Then, Chapter 4 disentangles the rationality of the traditional silvoarable system present in the agroecosystem until the mid-20th century. Finally, the conclusions from the investigation and the possibilities for further research are presented in Chapter 7, together with some final remarks.

I confess I am not charmed with the ideal of life held out by those who think that the normal state of human beings is that of struggling to get on; that the trampling, crushing, elbowing, and treading on each other's heels, which form the existing type of social life, are the most desirable lot of human kind, or anything but the disagreeable symptoms of one of the phases of industrial progress.

[…]

But the best state for human nature is that in which, while no one is poor, no one desires to be richer, nor has any reason to fear being thrust back, by the efforts of others to push themselves forward.

[…]

If the earth must lose that great portion of its pleasantness which it owes to things that the unlimited increase of wealth and population would extirpate from it, for the mere purpose of enabling it to support a larger, but not a better or a happier population, I sincerely hope, for the sake of posterity, that they will be content to be stationary, long before necessity compels them to it.

[…]

It is scarcely necessary to remark that a stationary condition of capital and population implies no stationary state of human improvement. There would be as much scope as ever for all kinds of mental culture, and moral and social progress; as much room for improving the Art of Living, and much more likelihood of its being improved, when minds ceased to be engrossed by the art of getting on.

John Stuart Mill, *Principles of Political Economy* ("Of the Stationary State")

una mirada desde la alcantarilla
puede ser una visión del mundo

la rebelión consiste en mirar una rosa
hasta pulverizarse los ojos

Alejandra Pizarnik, *Árbol de Diana*

Chapter 1: Theoretical Foundations

In this chapter I will introduce the main scientific perspectives that constitute the theoretical background of this work. The aim is not to provide a profound description of each of them, but to expose those elements of greater importance for understanding where is located this investigation within the domain of the social sciences in a mix of History, Economics, Anthropology and Ecology; and how the different approaches presented have guided and contributed to the historical analysis carried out.

First, I will make a brief introduction to the fields of Environmental History and Ecological Economics, together with the theory of Social Metabolism, which conform the general background, the basic worldview to perceive Society-Nature relations and socioeconomic systems. Secondly, Agroecology is presented as the scientific approach to understand the ecological functioning of agricultural systems. After these two perspectives, somewhat more focused on the material dimension of the economic and agricultural processes, another two theories will be introduced, with a greater attention given to cultural, social, intangible dimensions. Thus, thirdly I will expose the theories of Biocultural Heritage and Landscapes, which highlight the relevance of historical biophysical analysis as a way to approach to traditional knowledge. Finally, the field of Peasant Studies and the theory of Peasant Economy will be introduced, which offers an alternative rationality to understand the organization of productive systems.

1. *Environmental History, Ecological Economics and Social Metabolism.*

Environmental History (González de Molina & Toledo, 2011) and Ecological Economics (Costanza & Haeckel, 1996; Daly & Farley, 2011) start from the premise that societies and economic systems are inserted in and fundamentally linked to their natural environment. Introducing this elemental fact is what distinguishes them from conventional approaches in Economics and History. They are biocentric fields of study, rather than anthropocentric, understanding that the survival and welfare of human beings is conditioned by the survival and well-being of all living beings with whom we coexist and that make life possible on Earth (Costanza & Haeckel, 1996; González de Molina & Toledo, 2014). Against the modern dichotomy that separated Humanity and Nature (Moore, 2017), they defend the existence of one single socioecological system, in which human societies and natural environments are interrelated and coevolve and thus, the history of humanity cannot be understood without taking into consideration its relations with the environment.

One way of understanding the Humanity-Nature relation is provided by the theory of Social Metabolism (González de Molina & Toledo, 2014). The idea of the Social Metabolism is derived from Marx, who used the term “metabolism” for describing the relation that was established between humans and nature through the process of labour (Foster, 2000; Martinez-Alier, 2013). The sociometabolic perspective focuses on the material base of the relations between societies and nature, the flows of energy and materials that societies exchange with their environment. The metabolism of societies is a dynamic process through which Society and Nature determine each other. This relationship between human beings and the environment that surrounds them is mediated by social institutions and cultural practices. Thus, for assessing the metabolism of socioecological systems it is important to pay attention not only to the biophysical flows, but also to the institutional and cultural dimensions that shape these flows.

Historically, three main metabolic modes or regimes can be distinguished:

i) The Cinegetic or Extractive Mode of Social Metabolism, characteristic of hunter-gatherer societies and based on the appropriation and consumption of elements from the ecosystem. It was the dominant social metabolism until the Neolithic Revolution some 12,000 years ago. The social forms of organization associated to this social metabolism are the family, the band and the tribe. Ideologically, Human-Nature relations were governed by a kind of traditional ecological knowledge now defined as “sacred ecology” (Berkes, 2008), a cosmovision that considered no separation between humans and nature, that attributed life and spirit to the environment, and infused nature with religious, ethical and moral considerations.

ii) The advent of agriculture gave place to the Organic or Agrarian Metabolism, based on the domestication of nature, the transformation of landscapes, and the use of solar energy (mainly through agricultural production) for the appropriation of resources. The characteristic forms of social organization of this social metabolism are seniorities, chiefdoms, States and empires, even though domestic units and communities played a key role in the organization of agricultural production. Peasantry, carrying out the agricultural activities, was the most important social category. Markets gained importance but still had a secondary role in the process of distribution of goods, networks of mutual support were organized to guarantee social subsistence, and powerful classes survive through the appropriation of surpluses. A cosmovision of solidarity between humans and nature conducted their relations, and the local ecological knowledge accumulated through practice and transmitted across generations was a key element for the survival of the population.

iii) With the Industrial Revolution a new mode took place that extends until current times. The Industrial Metabolism is based on the use of mineral and fossil sources of energy that helped to expand the social metabolic processes of appropriation, transformation, circulation, consumption and excretion of energy and materials. Capitalism shapes the social organization, with the organization of production in factories, the individual as the main economic agent, and the distribution process ruled by markets. The relationship of humans with nature is based on the idea that humans dominate nature. Anthropocentrism and the search of monetary profit and improved material wellbeing lead to the consideration of nature as a mere factor of production.

Each of these sociometabolic regimes, predominant in different historical periods, entailed a distinct Human-Nature relationship that includes not only the biophysical dimension, but also certain social organization and cultural structures that shape the socioecological systems and characterize the metabolic modes.

With the advent of Capitalism and the Industrial Metabolism a *great transformation* occurred (Polanyi, 2003). It is not by chance that economic history and the history of economic thought take this period as their starting point. Not because there was no economy before. Understood in real or substantive terms (Polanyi, 1957), as the way societies obtain and guarantee their material living, there was certainly economy before:

any form of human subsistence requires an economic activity, a social metabolism. However, during Modernity starts the separation of the economy as an independent and autonomous sphere (Dumont, 1980; Polanyi, 2003). Markets, technological innovation and economic growth became the ruling and driving forces of economics and society. The conventional economic theory has been built over the assumptions that markets are the social institution that should govern the distribution of resources and there should be no interference in their functioning; that the continued economic growth is possible and desirable, and that the economic system is independent of the natural environment or able to overcome the possible environmental constraints thanks to technological innovation.

Ecological Economics disputes these assumptions (Costanza & Haeckel, 1996; Daly & Farley, 2011; Georgescu-Roegen, 1975). Reintroducing human societies and economic systems as subsystems in the biosphere implies introducing limits on the economic activity that societies can carry out without risking their sustainability. Economic systems are open systems that exchange energy and materials with their environment (Kapp, 1994) and economic processes are subject to the second law of thermodynamics, the Entropy law (Georgescu-Roegen, 1971). Introducing the energy analysis in the study of agricultural systems and their historical transformations is of utmost relevance, since agriculture has the potential to be a net energy supplier for the economic system, but with the spread of the Green Revolution in the second half of the 20th century it has been transformed into an energy sink, demanding more energy than it produces and using inputs from non-renewable resources (Leach, 1976; Naredo & Campos, 1980; Pimentel et al., 1973; Puntí i Culla, 1988).

2. *Agroecology*

Agroecology can be defined primarily as the application of ecological concepts and theories to the design and management of agricultural systems (Altieri & Nicholls, 2005; Gliessman, 1998). However, this discipline, whose origin can be traced back to the first decades of the 20th century, has broadened its perspective in recent decades adding social dimensions on its object of study.

Initially, agroecology was a combination of ecology (the functioning of ecosystems), agronomy (the management of agricultural systems) and some economics (the monetary dimension of agriculture as an economic activity) (Dalgaard, Hutchings, & Porter, 2003;

A. Wezel & Soldat, 2009). However, from the last decades of the 20th century agroecology has consolidated as a food production system alternative (and opposed) to industrial agriculture. The agroecological approach takes into consideration not only the agricultural process of food production, but expands its object of study towards the whole agrifood system, including concerns over social justice and cultural awareness (Altieri & Nicholls, 2005; Francis et al., 2003; Gliessman, 2015; Holt-Giménez & Altieri, 2013). Thus, agroecology enlarged towards a system-wide approach, understanding that only by assessing the interaction of all the components of the food system (agricultural production, economic structures, power relations, access to knowledge…), a fundamental agricultural change towards sustainability can be achieved. In order to transform profoundly the model of industrial agriculture, the whole socioeconomic context in which it operates needs to be transformed too.

Similar to the theories of Social Metabolism, Environmental History and Ecological Economics that aim to address the sustainability problems of our current socioecological system by transforming the way we understand Human-Nature relations and the functioning of our economic system, Agroecology also aims to address the sustainability problems of our current agricultural systems by transforming the way we understand the functioning of agroecosystems.

In the search of knowledge on how to design and manage sustainable farm systems, agroecology turns its eyes towards traditional agricultural agroecosystems (Altieri, 2004; Francis et al., 2003). Farm systems are the result of the coevolution of natural and social systems. Some of the generally shared characteristics of the traditional agroecosystems previous to the Green Revolution make them especially relevant to confront the unsustainability of modern industrial agriculture. Given that the unsustainability of modern agriculture is linked to the excessive use of industrial inputs, the expansion of monocultures and the primal profit orientation, traditional agricultural systems that minimize the use of external inputs, rely on crop diversity and multiple land uses, and aim to maintain the productive capacity of the agroecosystem and its resilience, are of especial interest for an agroecological transition. Furthermore, the knowledge associated to the adaptation to local conditions and to the autonomous ecosystem management (Vandermeer, 2011) is of great value for the future design of a sustainable agriculture. Generally, traditional farming systems have been able to meet the subsistence needs of the population linked to them, providing multiple goods and services while sustaining biodiversity. They have been adapted to a wide diversity of environments, being able to maintain their productive capacity without modern agricultural inputs and technologies. The persistence of many traditional agricultural systems nowadays, that have been able to endure over generations adapting to the changing socioecological context, is an evidence of their sustainability and resilience, and future agricultural innovation should combine the knowledge accumulated on these traditional agricultural practices (Koohafkan & Altieri, 2017). However, while some traditional agroecosystems persist nowadays, another large part of these farm systems has disappeared as a result of the spread of the Green Revolution or is disappearing due to economic and ecological pressures (Koohafkan & Altieri, 2011). The significance of this loss is not only because of the ecological consequences of transforming potentially sustainable agroecosystems that were created through a long process of socio-ecological coevolution into unsustainable farm systems that can be environmentally harmful, and disregard local natural resources; but there is also an important loss of knowledge about the local environment and those social practices and strategies that created and sustained traditional farm systems and provided the means of subsistence of the local population.

3. Biocultural Heritage and Landscapes

The search of valuable knowledge in traditional agricultural systems carried out by agroecological approaches is also defended by the theoretical perspectives of the Biocultural Heritage and Biocultural Landscapes. The idea that there is an indissoluble link between biological and cultural diversity was drawn from the fields of ethnoecology and ethnobiology, and gave birth to the concept of biocultural diversity, which embraces "the diversity of life in all its manifestations: biological, cultural and linguistic" (Maffi, 2012). Thus, the term "biocultural" refers to the consideration of socio-ecological systems as a whole in which humans and nature coevolve.

As any other species, human beings depend on their capability to adapt to the natural environment, and on the knowledge accumulated through their experience as individuals, communities, and species. The history of life on Earth can be characterized as a process of biological and cultural (Loh & Harmon, 2014) evolution and diversification in which each species adapts to, is transformed, and transforms its surrounding environment. With respect to human beings, there is a key process of diversification and coevolution between human communities and their environments that started around 12,000 years ago with the origins of agriculture. Through agricultural development humans adapted their productive systems and practices to the local environment that, at the same time, has been transformed. Thus, traditional agricultural systems can be considered a reservoir of our species memory (Toledo & Barrera-Bassols, 2008): a collection of ecological knowledge, experiences and procedures that have sustained our survival in relation with nature.

The biocultural heritage is particularly embedded in traditional agricultural landscapes and biocultural landscapes. The continuous interactions between human communities and nature through the domestication, variation and introduction of species, the transformation of the geomorphology, the implementation of water management systems and the use and promotion of certain environmental elements and features, has often created resilient landscapes of great biological and cultural diversity (Agnoletti & Emanueli, 2016). The importance of these landscapes is not merely as relics or vestiges to be kept in a showcase. Biocultural landscapes contain a history of human evolution, of adaptation strategies, technological innovations, and social values. They contain our species memory and, in the current context of ecological crisis, they constitute bio-cultural refugia (Barthel, Crumley, & Svedin, 2013), places in which to find shelter in periods of struggle, to find learnings that help us to deal with adverse conditions. The importance of rediscovering the knowledge deposited in this biocultural heritage and landscapes stems from the need to maintain biocultural diversity and enhance the synergies between cultural and biological diversity.

4. Peasant Economy

The definition of peasant as an analytical category has been largely debated and is still contested (Bernstein, 2009; Bernstein & Byres, 2001; Edelman, 2013; Shanin, 1982). Traditionally, the debate has turned around the opposition Lenin versus Chayanov, discussing whether peasants were part of a historical process of economic and social differentiation (and thus belong to a pre-capitalist condition that would eventually disappear), or if they constituted a coherent social type (with a distinctive economic logic and certain characteristics suitable to describe peasants anywhere and anytime). Nowadays, the use of the term “peasant” is considered to be highly romanticised and ideologically loaded (Bernstein, 2010; Edelman, 2013). However, when clearly defined the term “peasant” can be a useful analytical category.

The literature on peasant studies is long, but in this work we will focus on the productive principles associated to this category: the peasant economy. This work is aligned with the Chayanovian perspective (Chayanov, 1966) and considers that the peasant domestic unit of production is not governed by the same rationality as a capitalist agricultural exploitation. One of the characteristics that defines peasants is that they maintain a relation of ‘dependent autonomy’ (Narotzky, 2016). Peasant economies are tied to a wider socioeconomic system, but are not completely determined by it. This situation is due to a great extent to the fact that peasant production units have another two important characteristics: they own their means of production, and they do not depend on hired labour because the production is organized and carried out by family labour. In this sense, their functioning is similar to a ‘domestic mode of production’ (Sahlins, 1976), with a strong influence of kinship relations and a primarily subsistence orientation. Thus, the peasant production is not directed towards accumulation and profit maximization. The principles that govern the productive decisions of the peasant farm are, according to Chayanov, two balances: the labour-consumer balance, and the utility-drudgery balance. Briefly, they mean that in a domestic peasant unit there will be a correlation among the available family labour used and the consumption needs of the family unit, so that the basic needs of the family as a whole are satisfied. Any effort will be done if needed until a basic subsistence level is achieved, since the utility of the extra production obtained until that point will be high. However, further increases on the production will be carefully assessed considering the effort needed and the utility obtained.

Following Van der Ploeg (2013), another set of balances can be added following the chayanovian perspective to obtain a more complete analysis of peasant agriculture. Even though a balance autonomy-dependency is explicitly mentioned, it is possible to consider that all the following balances are interrelated and aim ultimately to guarantee that a certain autonomy is maintained, thus preserving the dependent autonomy relation of peasantry. These additional balances are between: people and living nature, production and reproduction, internal and external resources, scale and intensity, and the already mentioned balance between autonomy and dependency.

The perspective on peasant economy provides an economic rationality different from the dominant capitalist one. It considers that agricultural production is organized according to other aims than profit maximization, and that the economic organization can be done beyond market mechanisms. Thus, it provides a tool that helps analysing the agricultural economy from a substantive point of view (Polanyi, 1957).

5. *Raising the theoretical grounding*

Every scientific investigation starts from a certain theoretical background that determines the approach to the subject of study, the analytical tools to be used, and the expected results. In this case the theoretical starting points of this thesis are the fields of Environmental History, Ecological Economics and Social Metabolism, and Agroecology. These theories provided the background on which the methodology developed by the SFS was sustained and therefore, they lay the foundations of the energy and nutrient balances analysis. However, this scientific research has been a reflexive process (Davies, 2008; Finlay & Gough, 2003; Harding, 1987) in which the object of study and the researcher influenced each other. As the investigation on the historical transformations of the agroecosystem of Les Oluges evolved, so did the theoretical foundations that sustained it. The biophysical analysis of the energy balances of Les Oluges showed a striking characteristic of the agroecosystem of Les Oluges: the particular crop pattern of the silvoarable system combining cereals and woody crops. This specificity had been also noticed before by Enric Tello in his research on La Segarra (Tello, 1995), and probably it was a mix between his long held curiosity and my personal tendency towards more cultural, abstract issues that led the investigation to delve into the biocultural arena. Thus, the analysis of the nutrient balances that is presented on the third chapter, is already a work that links more explicitly the biophysical and cultural dimensions of the management of the agroecosystem, connecting the nutrient balances with the fertilising practices of each point of time studied. However, the stand on the Biocultural Heritage and Landscapes is more evident in Chapter 4, when it joins with the Peasant Economy approach in the analysis of the traditional intercropping systems as a final step of the analysis of Les Oluges.

Despite their diverse origins, the theories presented in this chapter conform a sound theoretical background. They emphasize different dimensions of socioecological systems, but share some basic assumptions, such as acknowledging the existence of inextricable links between humans and nature; and considering the complexity of socioecological systems, not trying to reduce the reality to more formally manageable structures, but acknowledging the epistemological limitations of separated academic fields and defending the importance of the inter- and multidisciplinarity and the dialogue between scientific disciplines and with the practical or symbolic know-how of peasants. Furthermore, they all have a critical background, not only because they point out what is wrong in our current Human-Nature relations, but they also propose means to transform that situation and achieve a better future.

Chapter 2: More than energy transformations: A historical transition from organic to industrialised farm systems in a Mediterranean village (Les Oluges, Catalonia, 1860-1959-1999)[3]

Abstract

The analysis of energy efficiency of agroecosystems from a sociometabolic perspective is a useful way to assess the sustainability of farm systems. In this chapter we examine the transition of a Mediterranean agroecosystem from an organic farm system in the mid nineteenth century to an industrialised one at the end of the twentieth century by means of the technologies and ideology of the Green Revolution. Given that many of the world's agricultural systems have experienced, or are currently experiencing this transformation, our results are relevant for building more sustainable agricultural systems in future. Our results highlight the relevance of livestock density, and the flows of biomass reused and unharvested biomass as key elements affecting the sustainability of the agroecosystem not only from a socioeconomic perspective, but also from an agroecological point of view. Additionally, from a biocultural perspective our investigation sustains the relevance of the study of traditional farm systems for the development of a sustainable agriculture.

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As corresponding author, I led the publication of this work in the *International Journal of Agricultural Sustainability.* My main contributions were the elaboration of the energy balances of 1860 and 1959, helping Xavier Cussó with the elaboration of the energy balance of 1999. I also wrote the whole article and the appendix, after a teamwork-process of discussion of the results obtained. Roc Padró, Inés Marco and Claudio Cattaneo introduced me and supported me in the elaboration of the energy balances. José Ramón Olarieta, Ramón Garrabou and Enric Tello provided the historical sources of Les Oluges, their knowledge about La Segarra, and their advice as experienced researchers.

1. *Introduction*

The need to build more sustainable agricultural systems, able to feed a growing population in an era of climate change and biodiversity depletion, is a major concern (Pretty et al., 2010). Current industrial agriculture heavily depends on fossil energy and does not seem adequate for achieving this goal in the long term. Conversely, there is a growing interest in agroecology and innovative ways to update and develop the bio-cultural knowledge embedded in traditional organic farm systems in order to search for a more sustainable agriculture (Altieri, 2004; Altieri & Nicholls, 2005; Gliessman, 2015; International Assessment of Agricultural Knowledge, Science and Technology for Development [IAASTD], 2009; Koohafkan, Altieri, & Gimenez, 2012; Schutter, 2010; Toledo & Barrera-Bassols, 2008; UNCTAD, 2013; Vandermeer, Smith, Perfecto & Quintero, 2009; Wezel et al., 2014).

This work seeks to add some knowledge about the basic features of sustainable farm systems by adopting a historical approach based on a sociometabolic analysis of agroecosystems (Fischer-Kowalski & Haberl, 2007; González de Molina & Toledo, 2014; Haberl, Fischer-Kowalski, Krausmann, Martínez-Alier & Winiwarter 2009). Many of the world's agricultural systems have experienced, or are currently experiencing similar transformations, by means of the technologies and ideology of the Green Revolution, that our historical case study underwent from the mid-twentieth century onwards. Traditional peasant management of agroecosystems relied on the use of local resources and remained within its biophysical constraints. They performed multiple uses and combinations of land covers, developed complex associations of crops and polycultures, recycled many by-products, and kept the use of external inputs at low levels (Gliessman, Engles & Krieger, 1998; Plieninger, Höchtl & Spek, 2006). All these components of integrated management of agroecosystems were substituted throughout the industrialisation of agriculture by the expansion of monocultures, and a high dependence on fossil-based external inputs. A much more single-minded management that was mainly focused on the target of increasing labour productivity, maximising land yields and generating short-term profits, replaced past organic traditional management of agroecosystems that kept an integrated management among living funds (population, land, livestock and farm-associated biodiversity). The spread of monocultures and mechanization, the extensive use of chemical fertilizers and biocides, and the increase of livestock density based on purchased feedstuff in modern industrial agriculture and animal farming have been linked to ecological problems of pollution and unsustainability, such as the degradation of soil quality, water eutrophication, greenhouse gasses emissions, increased dependence on non-renewable resources and fossil fuels, and loss of genetic diversity, resilience and ecosystem services provision (Altieri & Nicholls, 2005; Conway & Pretty, 2009; Foley et al., 2005; Gliessman, 2015). Furthermore, industrial farming systems and food production are also associated with global economic inequality and human health problems (Horrigan, Lawrence, & Walker, 2002; Johns & Eyzaguirre, 2006; Patel, 2012b; O. De Schutter, 2010; Tilman & Clark, 2014).

In this chapter we analyse the socio-ecological transition of the farm system of Les Oluges, a village located in the inland semiarid plain of Catalonia (Spain), from the mid-nineteenth century to the end of the twentieth century. This time span focuses on the transformation from an organic traditional farm system before the arrival of the Green Revolution in the mid-20th century to an industrialised agriculture by the end of the century, when this industrialisation was completed and reached its zenith. Our analysis reflects that the full industrialisation of the agroecosystem undermined its sustainability due to its lower energy efficiency, its greater dependence on external inputs and fossil fuels, and its reduced capacity to host associated biodiversity. The beginning of the 21st century would have inaugurate a new land-use regime characterized by an increased globalisation of sociometabolic flows (Guzmán et al., 2018; Soto et al., 2016), a greater efficiency of external inputs (Pellegrini & Fernández, 2018), as well as an spread of environmental awareness (Jepsen et al., 2015) that should be further studied.

In the following section we introduce our sociometabolic methodological approach applied at the farm community level on a municipal scale that helps us to understand agroecosystems as cultural landscapes (Antrop, 2005) shaped by human knowledge and labour. This approach allows us to analyse agroecosystem changes not only from a purely biophysical standpoint, but also looking at the social traits that fostered the transition towards increasingly unsustainable farm systems. Then, we outline the features of the case study and the sources used. In the second section we present the results, mainly looking at the changing structure of energy fund-flow patterns of these agroecosystems, and their ensuing energy returns on investment at three different points of time (1860, 1959 and 1999). In the third section we discuss our results by comparing them with another case study in Catalonia (Spain) so as to highlight some key features and determinants of the sustainability of these farm systems. To conclude we emphasise the importance of livestock management, the dependence on external inputs, and local adaptation to biogeographical natural resource endowments for the agroecological efficiency of farm systems.

2. *Methodology and sources*

2.1. Methodology

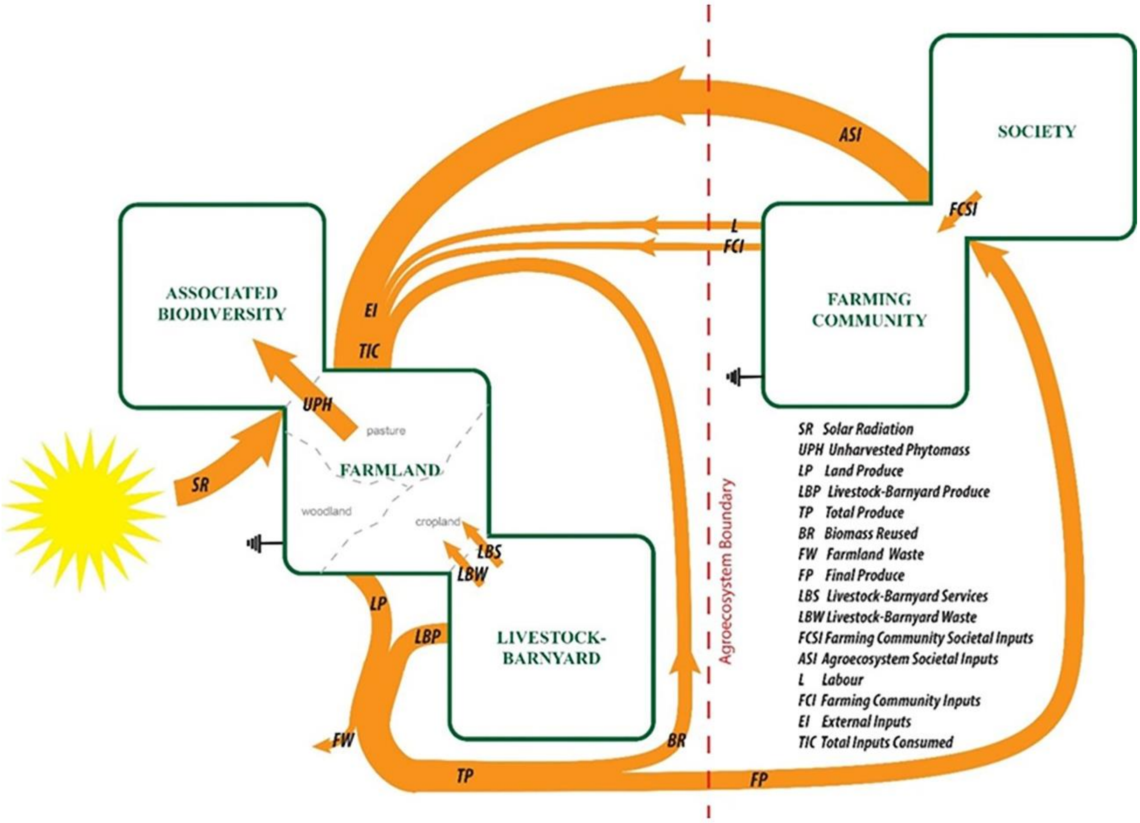
The methodology applied in this study has been thoroughly explained in previous works published by the international research project on Sustainable Farm Systems (SFS) (Galán et al., 2016; Gingrich et al., 2018; Guzmán & González de Molina, 2015; Guzmán, González de Molina, Soto Fernández, Infante-Amate, & Aguilera, 2017; Tello et al., 2016; Tello et al., 2015), which has been applied to different case studies around the world on various spatiotemporal scales. The basic modelling follows Georgescu-Roegen's distinction between funds and flows (1971), and establishes a way of accounting for the energy transformation and circulation that characterises the structure and functioning of farm systems from an agroecological perspective. Funds are defined by their capacity to transform biophysical flows and provide goods and services useful to farmers and society. Funds can only transform energy flows at a given rate, and need an energy investment if they are meant to keep their capacity and functioning over time (Giampietro, Cerretelli, & Pimentel, 1992). Different flows of energy are absorbed and provided by these funds, which opens a choice of either interconnecting them through an increasingly complex and integrated energy network or, on the contrary, keeping them separate into ever simpler and linear bioconversion chains. Here lies the most important feature that shapes the organic or industrial character of farming (Figure 1). The energy fund-flow pattern adopted determines the agroecosystem functioning, the ensuing landscape patterns and processes as the territorialized metabolic imprint, and the ecosystem services provided (Baró et al., 2016; Marull, Font, Tello, et al., 2016; Millenium Ecosystem Assessment, 2005)

The main living funds of an agroecosystem are: farmland, livestock, farming community and farm-associated biodiversity. They provide the basic structure of the agroecosystem from which different flows of energy carriers can be distinguished depending on their use, their aim, and their origin. In this regard, we understand the agroecosystem as an ecosystem that requires human labour, as information-as-structure in order to set up a purpose-oriented pattern of energy flows (Font et al., n.d.). Funds provide an output, but must not be degraded to maintain its productive capacity and stability over time

(Gliessman et al., 1998). Thus, the farming community is not only a fund but a free agent with a will that plays a fundamental role in the agroecosystem structure and functioning. As our model adopts the point of view of this farming community, we place it outside the agroecosystem boundaries together with the rest of society. The rationale behind this analytical decision is based on the fact that the farming community devises and manages the agroecosystem, introducing a set of External Inputs (EI), and receiving the useful flow we name Final Produce (FP). The labour provided by this farming community is also considered an External Input that takes into account the amount of embodied energy of the diet eaten by farm operators that is metabolised while working in the agroecosystem (Marco, Padró, Cattaneo, Caravaca, & Tello, 2018; Tello et al., 2015). Hence, setting the agroecosystem's boundaries in this way allows us to differentiate the energy fluxes that loop inside the agroecosystem as Biomass Reused (BR) from those that flow outside (FP), and those fluxes that come from outside the agroecosystem (EI). The sum of FP and BR equals the Total Produce (TP) obtained from the available farmland and livestock, i.e. the amount of energy that the agroecosystem generates and is either reinvested for the maintenance of its funds (BR) or diverted to meet human needs (FP). In some situations, a part of the TP does not perform any role as BR or FP; in such case, we consider this part as Waste (W). These are the main funds and flows considered from a socioeconomic perspective.

Additionally, in order to delve into the ecological dimension of agroecosystems other flows are taken into account. The actual Net Primary Productivity (NPP_{act}) considers the whole phytomass biologically produced by the existing land covers within the agroecosystem and throughout the year studied (Krausmann et al., 2013; Vitousek, Ehrlich, Ehrlich, & Matson, 1986) . It includes the biomass harvested, as well as the Unharvested Phytomass (UhP), which is the above- and below-ground biomass that remains in the agroecosystem independently of human aims. UhP is a valuable resource for maintaining farm-associated biodiversity and the provision of ecosystem services.

Figure 1. Diagram of the main funds and flows of an agroecosystem. Source: Tello et al. 2015, 2016.



Such a complex pattern of farming funds and flows cannot be assessed in energy terms by a single input/output ratio. Several interrelated EROIs (Energy Return on Investment ratios) are calculated in order to analyse the energy performance of agroecosystems. This multi-EROI approach considers the maintenance of the agroecosystem funds as the grounding requirement for a sustainable functioning of farm systems. Two different groups of EROIs are considered (Table 2). On the one hand, economic EROIs analyse the agroecosystem from an anthropocentric or socioeconomic perspective, linking the energy carriers produced by the agroecosystem that are available for human consumption with the energy purposely invested in it by the farming community and the society it belongs to. On the other hand, given that agroecosystems are not fully human-colonised ecosystems and depend to some extent on ecosystem services, a set of agroecological EROIs are also calculated. These consider the whole photosynthetic productivity of the agroecosystem (NPPact) beyond the biomass appropriated by humans in order to measure the space left to associated biodiversity and the provision of ecosystem services.

Table 2. Equations of the EROIs employed in the analysis. Source: Tello et al. 2015, 2016; Guzmán & González de Molina, 2015; Guzmán et al., 2017.

Economic EROIs	
Final EROI	$FEROI = \frac{Final\ Produce}{Biomass\ Reused + External\ Inputs}$
Internal Final EROI	$IFEROI = \frac{Final\ Produce}{Biomass\ Reused}$
External Final EROI	$EFEROI = \frac{Final\ Produce}{External\ Inputs}$
Final EROI on Labour	$Labour\ FEROI = \frac{Final\ Produce}{Labour}$
Agroecological EROIs	
NPP$_{act}$ EROI	$NPPEROI = \frac{NPPact}{Biomass\ Reused + External\ Inputs}$
Agroecological Final EROI	$AFEROI = \frac{Final\ Produce}{Unharvested\ \mathrm{Phytomass} + Biomass\ Reused + External\ Inputs}$
Biodiversity EROI	$Biod.\ EROI = \frac{Unharvested\ \mathrm{Phytomass}}{Unharvested\ \mathrm{Phytomass} + Biomass\ Reused + External\ Inputs}$

Final EROI (FEROI) measures the efficiency of agroecosystems as providers of energy carriers for human use taking into account the total investment made by farmers in it. This indicator can be broken down into Internal FEROI (IFEROI) and External FEROI (EFEROI). Each of these considers the returns of farming investment depending on whether it is the biomass produced by the agroecosystem and reinvested in it (BR) by farmers, or the external energy carriers (EI) that society and farmers invest in the agroecosystem from outside. Additionally, the Final EROI on Labour (FEROL) gives a measure of the energy productivity of farmers' labour invested.

From an agroecological perspective, NPP_{act}EROI assesses the whole energy return of the agroecosystem beyond a human provision perspective, which is in turn considered by the Agroecological Final EROI (AFEROI). The difference between AFEROI and FEROI is the consideration that the agroecosystem's capacity to provide flows of energy available for human use does not depend only on the human intervention and investment of energy inputs, but also on the unharvested biomass left in the agroecosystem without human intervention. The ratio AFEROI/FEROI provides a measure of human colonisation of the agroecosystem photosynthetic produce, so that when it equals 0 indicates that there is no human detraction at all, and it means a total human colonisation when it reaches a value of 1. Similarly, Human Appropriation of NPP (HANPP) measures the share of NPP_{act} that is controlled by humans for their own purposes (TP/NPP_{act}). Finally, Biodiversity EROI gives a measure of the agroecosystem's capacity to maintain farm-associated biodiversity through the availability of biomass flows not appropriated by humans per unit of the total energy carriers flowing through the agroecosystem as inputs for all heterotrophic non-domesticated living beings.

2.2. The village of Les Oluges in the inland dry plain of Catalonia

Les Oluges is a small village located at 490-650 m.a.s.l. in the Segarra County, in the province of Lleida (Catalonia, Spain) (Figure 2). It belongs to the so called *Poor* and *Dry Catalonia*, an area characterised by its aridity and its concentrated settlement pattern in contrast to the *Rich* and *Wet Catalonia* where average rainfall is higher and population was settled in a more scattered pattern (Burgueño, 2014; Garrabou, Planas, & Saguer, 2001; Vilá Valentí & Vila, 1973). The Sió River and the Riera de Vergós, two temporary creeks, are the only streams in the township. The Dry Mediterranean Continental climate of the area is characterised by cold winters and hot and dry summers that, combined with aridity (the period of water stress is from April to October (Garrabou, Naredo & Ávila Cano, 1999) jeopardise crop yields.

Figure 2. Maps of Spain and Catalonia (divided by Counties) showing the location of Les Oluges and the four municipalities of the case study in the Vallès County (Caldes de Montbui, Castellar del Vallès, Polinyà and Sentmenat) used for the comparative analysis. Source: our own.

The Segarra County had always had an agriculture mainly dedicated to cereals, but vineyards had also traditionally been grown to some extent (Vilá Valentí & Vila, 1973). From the eighteenth century vineyards grew in response to a regional commercial network in which liquors were sold abroad in order to import certain basic products that were needed to complement the frequently scarce yield from cereal lands (Tello, 1986). During the second half of the nineteenth century vine cultivation expanded in the area at the expense of forests in order to take advantage of the favourable market conditions when the *Phylloxera* plague began destroying all the vines in France (Pujadas i Rúbies, Solé i Roig & Pujadas, 1980). The vineyard boom lasted until 1894, when the *Phylloxera* plague reached the Segarra County.

In the first decades of the twentieth century, as a result of the end of the turn-of-the-century agrarian crisis, there was an increased specialisation toward cereal cultivation in the arid plains of Lleida province. Mineral fertilisers started to be used, together with new machinery powered by horses or mules (ploughs, reapers and threshers) and tractors. The creation of peasant unions and cooperatives helped the rapid spread of these new farm implements and industrial inputs[4] (Ramon Muñoz, 1999). This process was framed in a context of great political, social and economic changes in Catalonia and Spain. It was a period of industrialisation and rural exodus, in which agriculture was definitely changing its mainly subsistence and organic character by adopting a mixed organic-industrial one within a greater market orientation. Another important feature of this period was the beginning of livestock specialisation in some areas of Catalonia for which cereal-growing territories such as the Segarra County provided grain for feed (García Pascual, 1993; Pujadas i Rúbies et al., 1980; Pujol, 2002)

From the 1950s onwards the Green Revolution spread in Catalonia and Spain, agriculture became a completely industrialised activity, and rural population decreased steadily. Under the new technological package, cooperatives became increasingly concentrated and expanded an agribusiness scheme of contract farming and vertical integration (García Pascual, 1993). Following the specialisation trend in Catalonia and Spain, by the end of the 20th century the weight of livestock production also increased, becoming more dependent on feed imports (Soto et al., 2016). Furthermore, the inputs of nutrients from synthetic fertilizers in the Spanish territory reached their maximum in the decades of 1990 and 2000 (Guzmán et al., 2018). These trends can be appreciated in Les Oluges in 1999, a moment that could be characterised as a culmination of the Green Revolution.

2.3. Sources

In order to build the energy balance of Les Oluges c.1860 we used multiple historical records. The municipal land-use register (*Amillaramiento*) of 1860 gave us the pattern of land use of the existing farmland in the village. The local agricultural survey (*Cartilla evaluatoria*) of 1883 provided us with the information on cropland and livestock productivities and labour requirements. Livestock composition and human population data were obtained from the cattle census of 1865, and the municipal population register of 1870. Given that most of these historical documents were recorded for tax purposes, a concealment of information was expected. In particular, the total municipal surface registered in the 1860 *Amillaramiento* was significantly smaller than the real area of the village. Previous studies in other Catalonian municipalities showed that a great part of the

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[4] In the Segarra County the use of chemical and mineral fertilisers increased from 9.7 kg/ha of sown cropland in 1907 to 256.7 kg/ha in 1934 (Ramon Muñoz, 1999). New industrial machinery powered by mules was spread from 1920s onwards. However, according to the municipal agricultural surveys consulted, the first tractor was introduced in Les Oluges in 1957; ten years later there were 27 tractors registered in the village.

missing surface corresponded to woodland underestimation. The same assumption was made in this case, adding 345 hectares (18.4% of the total farmland area) to the area of woodland registered in the *Amillaramiento*. Despite this addition, the results obtained did not change significantly in terms of energy flows and returns (EROIs).

The data for the construction of the energy and nutrients balance of 1959 was obtained from the local cadastre of 1959, the municipal agricultural surveys of 1956 and 1959, the Spanish agricultural census of 1962 and from oral local surveys. During this period agriculture was experiencing a very rapid transformation with the spread of the Green Revolution. Thus, it was crucial to adjust the data as accurately as possible to the year studied that, nevertheless, will only reflect a short moment in this process of sociometabolic transformation of the agroecosystem.

For the balance of 1999 data was taken from the 1999 agricultural census. It was only possible to obtain municipal data for characterising the size and composition of the local funds (farmland, livestock heads and agrarian population), and the rest of the flows were estimated from provincial data.

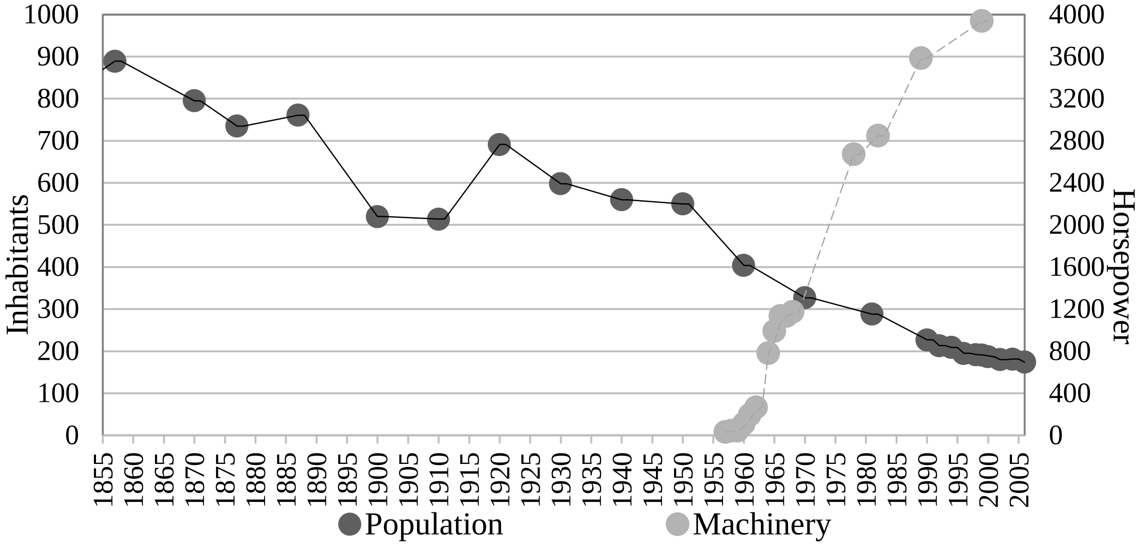
3. Results

3.1. Funds

3.1.1. Farming community and labour

From 1857 Les Oluges experienced a progressive process of depopulation that accelerated during the second half of the twentieth century (Figure 3). In the three time points studied the highest population density was registered in 1860, with 42 inhabitants/km^2. The number of Annual Working Units (AWU) needed in this period was significantly lower than the total population. However, this figure does not take into account the seasonality of agrarian work. Real labour demand would peak in the summer, corresponding to the period of cereal harvest.

Figure 3. Historical evolution of population (inhabitants) and mechanisation (total horsepower of tractors) in Les Oluges. Source: Our own, from Centre d'Estudis Demogràfics (http://ced.uab.es/en/infraestructures/banc-de-dades-espanya-i-catalunya/) and municipal agricultural surveys.



Population halved by 1959, and then again by 1999. This depopulation process was not an obstacle for the increase of cropland area and land use intensification. Three processes counterbalanced the loss of farming population and combined differently throughout two different stages. During the first half of the twentieth century the introduction of synthetic fertilisers allowed a yield increase (in the case of wheat, grain yield almost doubled from 1860 to 1959; see Appendix 1). Together with cropland diversification, and the help of improved machinery still powered by mules, all these improvements increased labour productivity as well. In 1959 the labour demand of the agroecosystem rose from 102 to 181 AWU. Crop diversification smoothed out labour seasonality and, with the new farm implements, reduced work requirements per hectare of cropland (from 0.28 GJ/ha in 1860 to 0.22GJ/ha in 1959).

A second stage towards industrialisation of farming ensued during the second half of the twentieth century. The expansion of cereal monoculture and the diffusion of tractors (Fig. 3) made possible a high increase in the total surface workable by a single agrarian worker: a five-fold increase from less than 9 ha per AWU in 1860 and 1959, to more than 45 ha in 1999. Consequently, population density decreased to a minimum of 10 inhabitants/km^2.

3.1.2. Farmland

In 1860 traditional organic farming involved a close integration among land uses that included cropland, woodland and pastureland. The most widespread crop system was the association of extensive grain growing with a relatively intensive vineyard cultivation (Figure 4a). This alley-cropping system mainly consisted of growing cereals in the land strips between rows of trees or vines, by sowing one and leaving another fallow alternatively. This associated crop pattern characterised the traditional cultural landscape of Les Oluges until the second half of the last century.

Figure 4.The changing agrodiversity of land-use patterns in Les Oluges, before and after the Green Revolution. a) Land uses in 1860; b) Land uses in 1959; c) Land uses in 1999. Source: Our own, from the sources detailed in the text.

Figure 4 (a)

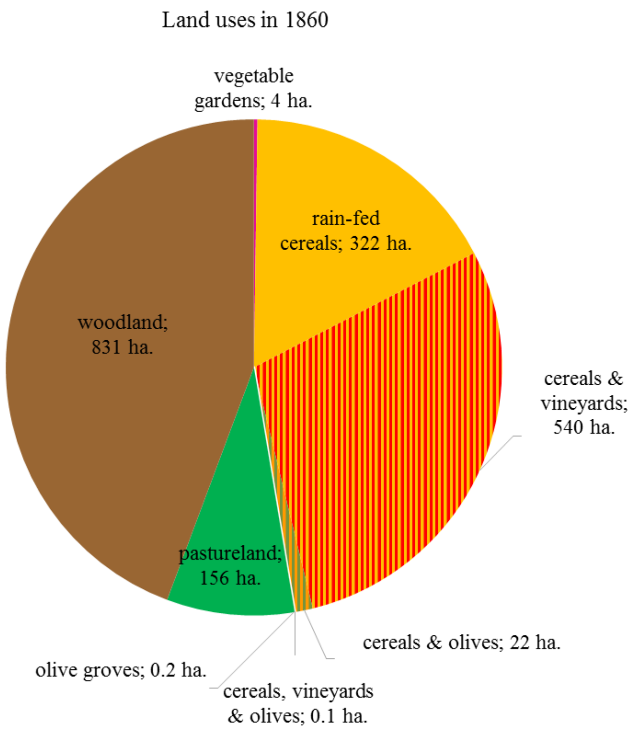


Figure 4 (b)

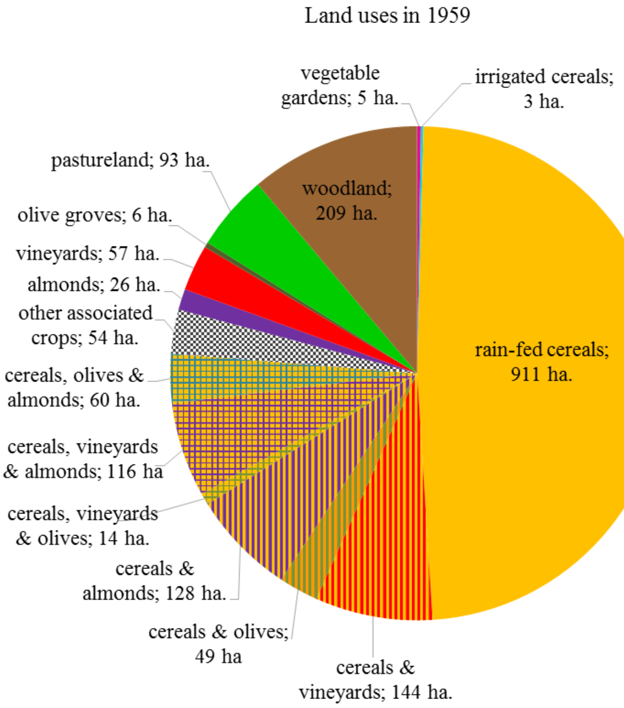
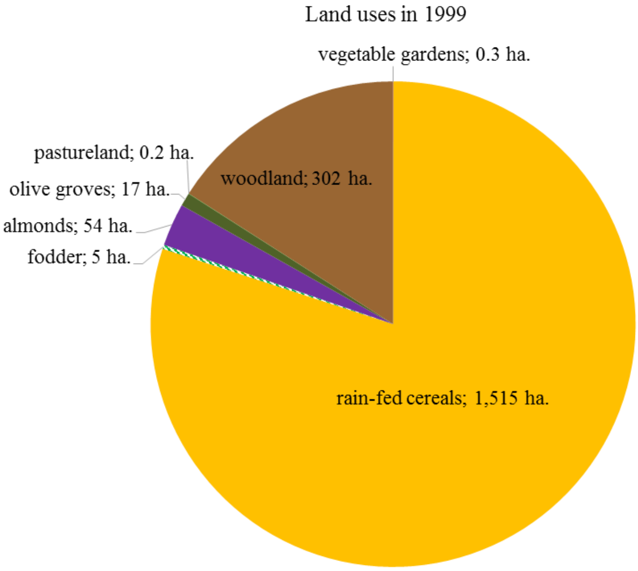


Figure 4 (c)



Cropland productivity was low because of the low yields (see Table 6 in Appendix), but also due to the widespread need for biennial fallow which left uncultivated one half of the cropland destined to cereals. This low productivity of cropland required, in turn, an intensive use of woodland for obtaining feed and organic fertilisers.

There was a fragile balance between cultivated and uncropped land that was broken by cropland expansion and intensification in the mid-twentieth century. From 1860 to 1959 (Figure 4a andFigure 4b) we observe a strong deforestation process that shrunk forestlands from 44% to only 11% of total farmland. Until that moment woodland and brushwood areas had been fundamental for providing additional feed to livestock, alternative fertilisers to the scarce manure, and firewood for domestic use. This, and the keeping of a site-specific peasant bio-cultural knowledge, may help explain why up to 1959 cropland expansion and intensification took place in Les Oluges by keeping a considerable area devoted to woody crops-cereal intercropping. This practice could somehow replace woodland resources providing animal feed and firewood through pruning. The result was a notable diversification of cropland through the introduction of new crops and a greater variety of alley-cropping associations (Table 3 and Figure 4b) that augmented the possibilities of the agroecosystem, even though water scarcity made it still necessary to keep 34% of the cereal cropland in fallow.

Table 3. The changing structure of Les Oluges agroecosystem's funds in 1860, 1959 and 1999. Source: Our own, from the sources detailed in the text.

Les Oluges - Funds							
Farming Community		**1860**		**1959**		**1999**	
Inhabitants		795		404		191	
Population density (inhabitants/km^2)		42		22		10	
Annual Working Units[1]		102		181		35	
Farmland		**1860**		**1959**		**1999**	
Cropland (ha)	Vegetable gardens	4.3	0.5%	4.6	0.3%	0.3	0.02%
	Irrigated cereals			3.1	0.2%		
	Rain-fed cereals	160.8	18%	511.7	33%	1,486.4	93%

	Fodder					5.1	0.3%
	Vineyard			56.5	4%		
	Olive groves	0.2	0.02%	6.3	0.4%	16.7	1%
	Almond trees			25.5	2%	53.9	3%
	Cereals & vineyard	405.2	46%	105.3	7%		
	Cereals & olives	16.6	2%	33.9	2%		
	Cereals & almond trees			86.8	6%		
	Cereals, vineyard & olives	0.1	0.01%	11.7	1%		
	Cereals, vineyard & almond trees			91.5	6%		
	Cereals, olives & almond trees			46.8	3%		
	Other associated crops			50.5	3%		
	Fallow	301.4	34%	538.3	34%	28.2	2%
	Total Cropland	**888.5**	**47%**	**1,572.7**	**84%**	**1,590.6**	**84%**
Pastureland (ha)		**155.8**	**8%**	**93.3**	**5%**	**0.2**	**0%**
Woodland (ha)		**830.8**	**44%**	**209.1**	**11%**	**302.2**	**16%**
Total Farmland (ha)		**1,875**		**1,875**		**1,893**	
Livestock		**1860**		**1959**		**1999**	
	Horses	2		3			
	Mules	56		120			

Draft animals (Heads)	Donkeys	146	10	
	Cows & oxen	20		
Livestock (Heads)	Cows & oxen			600
	Swines	165	80	6,588
	Sheeps & goats	325	310	500
	Poultry & rabbits	790	2,550	369,026
Total LU500		**151**	**124**	**3,082**
Total LU500/km^2		**8**	**7**	**163**

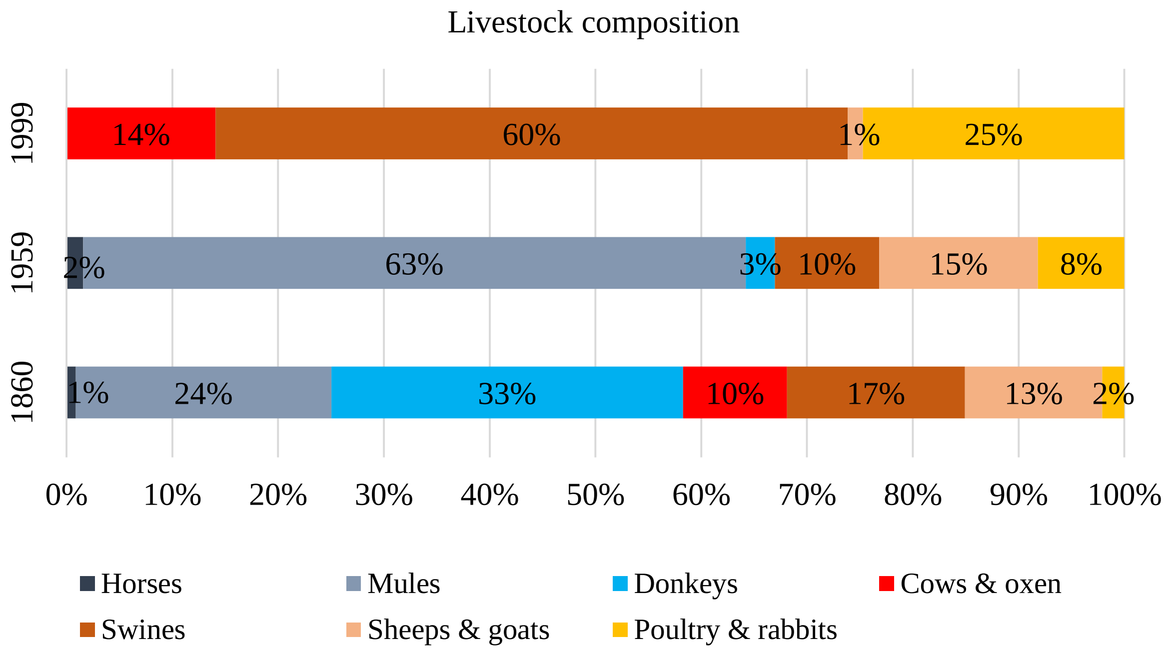
[1] As defined by Eurostat an Annual Working Unit expresses “the work performed by one person who is occupied on an agricultural holding on a full-time basis” (http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Annual_work_unit%28AWU%29)

Throughout the second half of the twentieth century pastureland disappeared while livestock density soared (Table 3). In 1999 livestock was confined into feedlots. Chemical fertilisers became an essential form of fertilisation along with manure, and tractors substituted for animal power. As a result, a great part of the internal flows of the agroecosystem was removed, largely simplifying the cultural landscape: 93% of cropland was devoted to grains in an almost complete homogenous cropland (Figure 4c), three fourths of which dedicated to barley.

3.1.3. Livestock

In 1860 Les Oluges had a relatively low livestock density of 8 livestock units of a standardised weight of 500 kg (LU500) per km^2 of farmland (Table 3) with a third of the livestock weight corresponding to donkeys (Figure 5). Donkeys were appropriate for a semiarid agroecosystem like Les Oluges in which feed was not abundant: they were less powerful animals than mules or horses, but also less demanding for their maintenance.

Figure 5. The changing livestock composition in Les Oluges, before and after the Green Revolution (1860-1959-1999). Source: Our own, from the sources detailed in the text.



In 1959 availability of synthetic fertilisers made it possible to partially overcome the previous limitations of natural resources. They allowed a significant cropland expansion and land-use intensification, whereas livestock density was reduced from 8 to 7 LU500/km^2, and donkeys were largely replaced by mules —a change required to power the new machinery used to carry out the crop expansion with a 49% decrease in the farming population. Given that pigs were mainly raised for domestic consumption, their number decreased with the decline in population. The increase of cropland productivity provided enough resources to feed the barnyard animals, and the use of woodland and pastureland decreased. The considerable increase in poultry and rabbits marks the beginning of a process of specialisation on fowl raising that the Segarra County has gone through from the mid-twentieth century onwards.

In 1999 livestock density skyrocketed to 163 LU500/km^2 (Table 3) largely due to the greater number of pigs and poultry, whose fattening in feedlots became completely industrialised. Draft animals disappeared, and sheep and goats slightly increased but had a testimonial role among livestock.

3.2.Flows and EROIs

From 1860 to 1959 and 1999 the agroecosystem became more productive in energy terms (Table 4). However, the composition of its energy fluxes changed significantly. In 1860 most of this produce came from woodland, while in the following years there was a process of ‘agriculturalisation’ (Guzmán & González de Molina, 2015) of farmland by which cropland increased its surface and became the main source of biomass production. The increase in cropland produce in 1959 was mainly due to cropland expansion, whereas in 1999 it was largely the result of the increase in cereal yields.

The TP appropriated was increasingly diverted to FP throughout the period studied. The back of that coin was the decrease of the biomass reinvested into the agroecosystem (BR) as feed and fertiliser. Between 1860 and 1959 in spite of the increase in the FP extracted, the flow of BR decreased in absolute terms in this same period. BR increased again in 1999, but only because of the rise of livestock density. The abandonment of the BR effort kept in traditional organic agroecosystems was only possible due to its replacement with EI. In 1860, EI came exclusively from the agrarian community, while in 1959 further EI were introduced from the rest of society in the shape of machinery and mineral fertilisers.

Table 4. Energy flows in the agroecosystem of Les Oluges village, before and after the Green Revolution (1860-1959-1999). Source: Our own, from the sources detailed in the text.

Les Oluges – Flows (in Gigajules)							
		1860		**1959**		**1999**	
NPP_{act}		**116,099.98**		**125,259.33**		**226,120.77**	
Unharvested Phytomass		**57,887.93**	50%	**51,130.70**	41%	**70,941.61**	31%
Total Produce	**Total TP**	**58,504.03**		**74,358.54**		**186,947.09**	
	Cropland	22,094.33	38%	67,303.58	91%	155,017.82	83%
	Pastureland	2,731.43	5%	1,635.97	2%	0.00	0%
	Woodland	33,386.29	57%	5,189.07	7%	161.34	0.1%
	Livestock	291.98	0.5%	229.92	0.3%	31,767.92	17%
	Total FP	**24,365.80**		**43,378.13**		**147,155.68**	

Final Produce	From cropland		3,200.18	13%	39,095.87	90%	115,226.42	78%
	From woodland		20,873.63	86%	4,052.34	9%	161.34	0.1%
	From livestock		291.98	1%	229.92	1%	31,767.92	22%
Biomass Reused	**Total BR**		**34,138.23**		**30,980.41**		**34,774.31**	
	Farmland	Total	11,658.13	34%	13,949.72	45%	9,102.89	26%
		Seeds	671.14	6%	2,001.96	14%	3,413.32	37%
		Buried biomass	4,123.00	35%	11,947.76	86%	5,689.57	63%
		Formiguers	6,864.00	59%				
	Livestock	Total	22,480.10	66%	17,030.69	55%	25,671.42	74%
		Feed from cropland	8,122.06	36%	11,778.10	69%	22,001.97	86%
		Feed from pastureland	5,549.81	25%	2,550.89	15%		
		Feed from woodland	7,481.08	33%	221.81	1%		
		Stall bedding	1,327.16	6%	2,478.89	15%	3,669.44	14%
External Inputs	**Total EI**		**1,273.25**		**6,602.63**		**266,313.31**	
	Agrarian Community	Labour	249.52	20%	351.72	5%	500.87	0.2%
		Residues	1,023.72	80%	520.23	8%		
	Societal inputs	Machinery			2,522.79	38%	60,606.16	23%
		Fertilisers and biocides			3,207.89	49%	14,014.85	5%

	Seeds					7,449.85	3%
	For livestock					183,741.93	69%
Livestock Services	**Total LS**	**3,102.16**		**9,072.99**		**37,294.33**	
	Manure	2,364.11	76%	8,458.68	93%	37,294.33	100%
	Draft Power	738.05	24%	614.31	7%		
Waste						**5,017.10**	

Table 5. Energy Returns on Investment ratios (EROI) in the agroecosystem of Les Oluges village, before and after the Green Revolution (1860-1959-1999). Source: Our own, from the sources detailed in the text.

EROIs		**1860**	**1959**	**1999**
Final EROI	FP/(BR+EI)	0.69	1.15	0.49
External Final EROI	FP/EI	19.14	6.57	0.55
Internal Final EROI	FP/BR	0.71	1.40	4.23
Final EROI on Labour	FP/Labour	97.65	123.33	4,204.45
NPP_{act} EROI	NPP_{act}/(BR+EI)	3.28	3.33	0.75
AFEROI	FP/(UhP+BR+EI)	0.26	0.49	0.40
Biodiversity EROI	UhP/(UhP+BR+EI)	0.62	0.58	0.19
AFEROI/FEROI		0.38	0.42	0.81
HANPP	TP/NPP_{act}	50%	59%	83%

Yet in 1959, the replacement of BR by EI was still in its infancy, and the absolute and relative amount of EI remained small. This explains that the FEROI (Table 5) increased between 1860 and 1959, since the unavoidable reduction in the return to EI (EFEROI) was offset by the IFEROI increase due to the simultaneous reduction of BR. This balance could be kept only as long as the agroecosystem maintained a mixed organic-industrial functioning. The replacement of BR by EI, became almost complete in 1999. From 1959 to 1999, FP increased threefold, but at the cost of an amount of EI forty times higher. Additionally, although most of the FP came from cropland, EI and BR flows were mainly directed to feed the livestock. As a result, the total energy spent doubled the energy content of the FP provided to society.

The great increase in livestock density and the replacement of BR by EI had an adverse outcome apart from the loss of energy efficiency. A new flow appeared: waste. This flux refers to resources which under a traditional organic management used to be recycled in the agroecosystem as organic matter stored in the soil, but now have no use or are produced in excess (i.e. surplus manure and crop by-products). The size of this flow is strongly determined by the assumptions made (see Appendix) given the lack of statistics on the pace at which reuse of by-products was given up; but ultimately its significance goes beyond its volume, since it denotes a significant eco-inefficiency of farm management.

Another relatively small flow in all three points in time that has a key importance is labour. Its relevance lies on being the main force that manages the agroecosystem, providing information and knowledge for its functioning in order to satisfy human needs. Labour productivity expressed by the Final EROI on Labour soared in 1999 as a result of the mechanisation of agriculture and industrialisation of livestock production. However, despite Les Oluges produced much more biomass energy in 1999 than in 1860, and with a greater labour productivity, its energy efficiency was lower. Only the IFEROI was higher in 1999 than in previous times, but this entailed the abandonment of an energy flow essential for the sustainable reproduction of agroecosystems: the BR aimed at maintaining soil living organisms and fertility, and integrating land uses.

The clearance of woodland area lessened the most important biological source of high-concentrated energy carriers, but the increase in cropland productivity balanced out this effect in total NPP_{act}. Yet NPP_{act}EROI highlights that the increase in the total biomass photosynthesised was attained at the cost of a massive unsustainable consumption of fossil-fuelled EI, which also decreased the energy efficiency of the agroecosystem. Higher yields at the expense of EI are also behind the evolution of AFEROI. The fact that it reaches a higher value in 1999 than in 1860 should be read carefully. Like the greater IFEROI of 1999, a higher AFEROI does not mean better ‘efficiency’ but rather the fact of extracting a FP six times larger from the farmland, while recirculating in it only 15% more UhP and BR than in 1860. The internal energy flows looped into the agroecosystem were greater than the energy content of the biomass extracted from it in 1860, but these internal flows were reduced in 1959 and 1999. Conversely, the lower AFEROI in 1860 reveals the great reinvestment of biomass flows needed to sustain the energy productivity under an organic farm management.

4. *Discussion*

4.1. The energy transformations of Les Oluges

The results obtained in Les Oluges in 1860 show an agroecosystem in which farmers were, as in any traditional organic agroecosystem, closely tied to their territory and constrained by its ecological features, to which they had developed biocultural adaptation strategies based on an integrated and (to some extent) extensive use of land (Pujol, 2001). Since aridity was the most important limitation and irrigation was not available for most of the land –or when available, it was only occasional—, agriculture needed to adapt to water scarcity. The widespread use of biennial fallow was the main response to this limitation. This dry-farming management allowed the soil to recover nutrients and to increase the amount of water stored in it (Garrabou, Naredo & Ávila Cano, 1999). Aridity also prevented land-use intensification by the introduction of legumes or fodder crops in formerly fallow land (Garrabou, 1978). This reduced the possibilities of feeding more livestock that could provide enough manure to fertilise more intensive crop rotations. Livestock density was similar or even a bit larger than in coastal Catalonia (Marco et al., 2018), but far from the 25 LU500/km^2 of Austria or some parts of the United States in the nineteenth century (Cunfer & Krausmann, 2009, 2015). Its composition was also an adaptation to the local ecological conditions. The difficulty in sustaining a sufficient livestock density made it necessary to draw upon woodland not only for providing enough feed, but also for supplementing the scarcity of manure by the traditional technique of *formiguers* –e.g. burning forest biomass in a set of small kilns, and ploughing the charcoal into cultivated soils (Olarieta, Padró, Masip, Rodríguez-Ochoa & Tello, 2011). The energy flows of 1860 show that forestland was an essential resource for the functioning and maintenance of the agroecosystem, providing soil nutrients, animal feed, wood, firewood and other by-products for domestic use (Iriarte Goñi, 2003). Livestock played a key role in integrating this agro-ecological mixed farming (Krausmann, 2004).

The intercropping system developed in Les Oluges was also a traditional adaptation to aridity. This association of perennial and annual crops was not only a diversification response to the risk of frequent harvest failures from the perspective of economic rationality, nor merely a way to take advantage of market conditions. This intercrop can be regarded as a wise management of the natural resource endowment that sought to attain greater agroecosystem stability by taking advantage of the agroecological synergies set among different land covers and plant root systems to improve yield stability, resistance to pests, and resilience to cope with adverse climate events. The greater complexity and heterogeneity of cropland also benefited farm-associated biodiversity (Alam et al., 2014; Altieri & Nicholls, 2002, 2004; Palma et al., 2007; Rigueiro-Rodríuez, McAdam & Mosquera-Losada, 2009). The relatively high population density of Les Oluges in 1860 (42 inhabitants/ km^2) is the midpoint between traditional intensive organic agricultures with a strong vineyard specialisation (60 inhabitants/km^2 or above) and the densities found in extensive cereal-growing regions of inner Spain (25 inhabitants/km^2 or below) at that time (Badia-Miró & Tello, 2014; Garrabou, Tello & Cussó, 2008).

The introduction of fertilisers, machinery, and new crops and seeds changed the agroecosystem of Les Oluges in 1959. They allowed for a partial substitution of BR by replacing the traditional labour-intensive techniques of fertilisation (the *formiguers*) and supplementing manure and fallow. In addition, tractors started to replace animal draught power. Thus, the agroecosystem was able to increase its cultivated area, to raise cropland yields and to provide more energy resources for human consumption (FP). But mechanisation also involved the removal of many dry-stone walls (Olarieta & Padró, 2016) as the old terraces were too narrow for the new machinery. The investment in these operations and the costs to the agroecosystem in terms of increased soil erosion and organic matter and nutrient losses still needs to be assessed.

The slight decrease of livestock density did not tame the increase in yields because the lower need for pasture was coupled with increased housing of animals and manure availability, and the agroecosystem started a process of increasing emancipation from the land (Mayumi, 1991) through a greater dependence on EI. Neither the lower population density was an impediment for the enlargement of cropland. Mechanisation increased productivity of labour and the maintenance of the intercropping system prevented the increase of seasonality, a clever Chayanovian improvement (Chayanov, 1966; Van der Ploeg, 2013). The enlargement of cropland and the remarkable deforestation of Les

Oluges in 1959 was also driven, by the increasingly stronger market connections. The improvement of the railway network and the boom of vineyard in the second half of the 19th century facilitated a greater market orientation of agriculture (Badia-Miró, Tello, Valls, & Garrabou, 2010), with the support, from the beginning of the 20th century, of peasant unions and cooperatives, which became a fundamental tool for the commercialisation of the agricultural inputs (mineral fertilisers and machinery) and produce (cereal grains and flour, and animal products) (Ramon Muñoz, 1999).

The agroecosystem of Les Oluges in 1959 was based on a mixed organic-industrial farming that made it possible to increase its energy efficiency and cropland productivity. However it would not be until 1999 that some of the former ecological constraints on farm management would be overcome. The spread of the Green Revolution technical package got rid of the main organic management practices (Soto et al., 2016; Guzmán et al., 2017). With the elimination of fallow and grazing land a great deal of the former land cost of agrarian sustainability (LACAS) (Guzmán, González de Molina & Alonso, 2011) has been transferred to other territories, while the agroecosystem of Les Oluges acquired the main features of a modern industrial agroecosystem: monoculture, mechanisation, dependence on external inputs and low labour requirements. In addition, livestock density soared, becoming a key element in the unsustainability of the agroecosystem (Soto et al., 2016). Traditionally farm animals had played an important role in agroecosystems as providers of multiple services and products (Krausmann, 2004). Paradoxically, while their weight in the agroecosystem's structure has vastly increased at present, triggered by the human dietary transition towards unhealthy levels of meat consumption (Smil, 2002; Soto et al., 2016; Tilman & Clark, 2014), their former integrating agroecological role has been lost. Furthermore, despite providing only 17% of the FP in 1999, most of the energy introduced and reinvested in the agroecosystem was aimed to feeding livestock, becoming a key determinant of the overall energy efficiency of the farm system.

Crop diversification was replaced by a cereal monoculture; the application of synthetic fertilisers boosted despite the greater availability of manure; livestock feeding in feedlots was decoupled from cropland; and the consumption of agrochemicals soared in order to tackle with the growing imbalances of this simplified agroecosystem that lost a great deal of the self-regulation capacity provided by its farm-associated biodiversity. Through these changes, the agroecosystem of Les Oluges became a net consumer of energy from the society with an EFEROI below one, while in 1860 and 1959 it had been a net producer of energy for the society.

Finally, the decrease of Unharvested Phytomass can be linked to a reduction of the agroecosystem's capacity to host biodiversity either belowground, in the soil food chains, or aboveground in the land cover diversity and species richness (Marull et al., 2017). A nature-based agroecosystem has been replaced by an industrial farming system relying on fossil fuel depletion.

4.2. Les Oluges in a comparative view

Previous studies carried out with this same methodology (Galán et al., 2016; Guzmán & González de Molina, 2015; Guzmán et al., 2017; Marco et al., 2018) allow us to compare the results obtained in Les Oluges, and better understand some of the determinants of the sustainability of agroecosystems. Here we will mainly focus on the contrast between Les Oluges and another Catalan case study: four townships in the Vallés county with an approximate total area of 120 km^2 (Sentmenat, Caldes de Montbui, Castellar del Vallès and Polinyà) (Figure 2). Vallès has been widely studied from a historical sociometabolic perspective (Badia-Miró, Tello, Valls & Garrabou, 2010; Cussó, Garrabou & Tello, 2006; Galán et al., 2016 Marco et al., 2018; Padró, Marco, Cattaneo, Caravaca, & Tello, 2017). It belongs to the wetter and wealthier part of Catalonia, and provides a particularly relevant contrast to compare with our semiarid case study.

Under organic farming conditions in mid-nineteenth century, Vallès was favoured by its climate conditions and proximity to Barcelona. Higher rainfall allowed for a more intensive land use, substituting fallow with crop rotations including leguminous crops (Garrabou & Planas, 1998). These provided soil fertilisation, feed for livestock, and more resources available for human use. Additionally, its proximity to Barcelona and its port was a driving force for market orientation and specialisation of agriculture. More than half of the cropland of Vallès was dedicated to vineyard in 1860, while in the same period in Les Oluges the expansion of vineyard reached only 46% of cropland and was grown exclusively in alley-cropping association with cereals and olives. Their socio-ecological endowment rendered higher energy efficiency in Vallès (with a FEROI of 1.03) than in Les Oluges. BR was the main flow invested in the sustenance of the agroecosystem, and it had to be much higher in Les Oluges than in Vallès in 1860. From the TP of the agroecosystem, Vallès invested 48% as BR, while in Les Oluges this percentage was 58%.

The situation changed after the *Phylloxera* plague that reached Vallès from 1883 and the Segarra County from 1894 onwards (JCA, 1911). Les Oluges followed the abovementioned process of deforestation and cropland expansion in which vines, together with other tree crops, maintained a significant role. In Vallès cropland area diminished, and rainfed cereals and pastureland took over most of the land previously dedicated to vineyards. Additionally, Vallès began a process of livestock specialisation producing dairy and meat for the nearby urban centres. From 1860 to 1950s FEROIs of Les Oluges and Vallès experienced opposite trends: energy efficiency diminished in Vallès (with a FEROI of 1.01) and increased in Les Oluges. This also holds true for the agroecological EROIs (AFEROI of Vallès was 0.49 in 1860 and 0.25 in 1956).

In 1999 the energy efficiency of both agroecosystems dropped. The lower energy efficiency of Vallès (with a FEROI of 0.22) was mainly due to its greater specialisation in livestock (with a livestock density of 241LU500/km^2, mostly swines). The expansion of forests on abandoned agricultural land in Vallès did not compensate for the homogenisation of land covers, polarised into urban (22% of total area), woodland (57%) and grain-growing monocultures (18%) (Marull, Pino, & Tello, 2008; Olarieta, Rodríguez-Valle, & Tello, 2008). The unbalanced livestock density in relation to cropland area led to a problem of an excess of manure produced.

Land uses also reflect the different socioeconomic structure of Vallès and Les Oluges. In Vallès population grew over the 20th century, and even though agriculturally active-population decreased, other economic sectors, such as industry and services, developed in the area. Conversely, Les Oluges remained based on agriculture and its population constantly decreased during the last century.

Despite the more adverse natural resource endowment and after a rather similar historical evolution in energy terms, Les Oluges reached a relatively greater energy efficiency than Vallès in 1999 mainly due to a lower livestock density.

These results are in line with the ones obtained at the state scale (Guzmán et al., 2017; Soto et al., 2016). Spanish agriculture has experienced large increases in livestock numbers, woodland area, and cropland productivity. However, the higher amount of BR and EI needed to feed livestock are among the main causes of the loss of farming energy efficiency throughout the twentieth century. Despite the abandonment of woodland and pastureland, UhP declined because of the higher proportion of biomass appropriated for human consumption (AFEROI), rendering a declining Biodiversity EROI.

5. *More than energy transformations*

The transformation of the agroecosystem of Les Oluges, and its comparative view with other case studies, bring to light three main ideas. Firstly, the importance of livestock density for the energy performance of agroecosystems stands out. The low energy efficiency of animals as bio-converters (Gliessman et al., 1998) imposes a considerable burden on any farm system, not only in energy terms but also regarding competition with land uses for human food (Guzmán & González de Molina, 2009). Past organic farm systems managed to override this burden by taking advantage of the use of animals as bio-converters of farm by-products or domestic residues that would otherwise be disposed of. Animals would also be fed from the less productive soils, such as grazing natural pastures in mountainous areas or shrub land, increasing the production obtained from these lands. This integration of livestock feeding into complex agroecosystems maintained a high land cover diversity able to host farm-associated biodiversity that enhanced the provision of regulatory and sustenance ecosystem services (Haberl, 2015; Marull, Font, Padró, Tello, & Panazzolo, 2016). Under the industrial functioning, the high density of livestock dependent on imported feed and the loss of livestock-farmland integration has affected the loss of energy efficiency of the agroecosystem. Livestock requires a great investment of energy and produces a relatively small amount of energy for satisfying human needs mainly focused on animal food products. Additionally, the industrialisation of livestock farming has led to severe agroecosystem degradation. Pollution by slurry from feedlots, and landscape biodiversity losses, are two clear examples of this socio-ecological deterioration (Naylor et al., 2005; Padró, Marco, Cattaneo, Caravaca, & Tello, 2017; Tilman & Clark, 2014).

Secondly, the intensive production of barley and deforestation in Les Oluges can be linked, at least from a theoretical perspective, to the very high levels of livestock density in Vallès, where feedlots rely on large feed imports and more than half of the land has been abandoned and spontaneously reforested. Contrary to the positive views of this transition, made possible in Vallès by the land sparing effect of intensive feed grain-growing in Les Oluges or similar areas, the crude fact is that biodiversity has been degraded in the former—a result that supports the alternative claims for a *land sharing* approach to nature conservation (Barthel et al., 2013; Bennett, 2017; Fischer et al., 2008). It is not only wild habitats that are important for the maintenance of biodiversity, but also the degree of human appropriation of photosynthetic capacity and the spatial disturbance patterns that take place in agroecosystems, which in turn give rise to diversification, heterogeneity and complexity of landscapes (Marull et al., 2016, 2018)

Thirdly, we found that mixed organic-industrial farm systems provide interesting examples of agroecosystems that made it possible to raise cropland productivity and thus overcome some bottlenecks of traditional organic farming, while keeping some energy-efficient balances agro-ecologically sound. These are nowadays called eco-functional intensification practices (FAO, 2013).

The example of Les Oluges in 1959 shows an interesting combination of modern innovations and traditional farm management methods based on local peasant knowledge. Use of relatively small amounts of synthetic fertilisers and machinery reduced the dependence on a limited amount of manure and animal draught force, overriding the LACAS (Guzmán & González de Molina, 2009; Guzmán et al., 2011). True, the introduction of inputs based on fossil fuels and non-renewable resources started an unsustainable path which would eventually lead to an extreme simplification of farmland and livestock processes as seen in 1999. However, in the mid-twentieth century the agroecosystem still retained important elements of its organic functioning. One of these was fallow. Even though this practice has long been deemed as a signal of backwardness in agrarian systems, it is still a convenient dry-farming practice in arid areas (Garrabou et al., 1999; Garrabou, Naredo, & Balboa, 1996). Additionally fallow land can be used as pasture or, when it is not used by livestock, it is made available for the associated biodiversity that provides important ecosystem services. Another important traditional feature of Les Oluges in 1959 was the maintenance and increased diversity of farming systems that intercropped vines, olives and almond trees with cereals. The reasons behind the maintenance and advance of this intercropping system need to be further studied (Vandermeer, 1989).

Fallowing and intercropping were two long-lasting traits of site-specific peasant knowledge in Les Oluges, and the whole Segarra County (Tello, 1986), that remained as sources of significant agro-ecological awareness until the dawn of the Green Revolution. The local impact of the European-wide agricultural crisis at the end of the nineteenth century gave rise to a growing presence of farmer unions, cooperatives and local public institutions. These organisations played an important role in making available new fertilisers and machinery to smallholders, and conducting research and experimentation on improved cereal seeds and animal breeds adapted to the local environment (Ramon Muñoz, 1998, 1999).

However, after the Spanish Civil War (1936-1939) this positive institutional environment disappeared. Free unions were banned, coops were tightly controlled by the dictatorship, and the former decentralised centres of scientific research, innovation and dissemination of agricultural knowledge were substituted by an authoritarian state-led model that spread the imported chemical, mechanical and biological technologies of the Green Revolution. Farmers did not play any active role in the progress and practice of this agricultural knowledge. The implementation of the Green Revolution came along in Les Oluges with the introduction of a new form of agricultural practice based on a foreign scientific knowledge that put the focus exclusively on cropland and labour productivities, disregarding the ecological specificities and reproductive necessities of each agroecosystem. This clearly contrasts with a traditional peasant knowledge that has been developed through generations and adapted to local conditions, which is knowledge- instead of input-intensive, and usually aimed at maintaining the productivity of the agroecosystem in the long run (Altieri, 2004; Patel, 2012; Pujol, 2001; Shiva, Rojas Rosales, & Guyer, 2007; Toledo & Barrera-Bassols, 2008). This cultural, technological, social and ecological transformation left its footprint on the landscape. The traditional intercropping system that depicted a landscape pattern in stripes disappeared together with at least part of its traditional biocultural heritage.

6. *Conclusions*

What, then, can be learned about the sustainability of future farm systems from this case study? The historical sociometabolic analysis of agroecosystems provides valuable insights into the elements that can enhance or degrade the sustainability of agroecosystems. Our case study of Les Oluges directs attention to three aspects. First, the increase of livestock density and the industrialised livestock management functionally disconnected with farming is an important driver for the loss of energy efficiency of modern agroecosystems. In order to build more efficient agroecosystems in energy terms, it is necessary to reduce livestock density and re-integrate its feeding sources with farming into more complex agroecosystems. Second, the harming consequences of substituting internal biomass reuse flows by external inputs, especially when these external inputs are based on non-renewable and pollutant sources like fossil fuels. The biomass recycled into the agroecosystems (both the reused and the unharvested biomass) is important for sustaining the productive capacity of their fund elements, and for the provision of ecosystem services that increase their resilience. This leads us to a third aspect: sustainable farm systems need to be locally adapted to their ecological conditions. In this regard, it would be worthwhile studying the biocultural memory (Toledo & Barrera-Bassols, 2008) of these Mediterranean traditional farm systems, recovering the local knowledge imprinted on agricultural landscapes. The complex intercropping systems developed in Les Oluges up to mid-twentieth century can be good examples to learn from.

Appendix to Chapter 2: Main assumptions for the calculation of the energy balances of Les Oluges in 1860, 1959 and 1999.

The calculation of the energy balances of Les Oluges has been made following some of the main criteria and assumptions made in the previous study of Vallès (see the Supplementary Material in Marco, Padró, Cattaneo, Caravaca, & Tello, 2017) and the working papers of Aguilera et al., (2015) and Guzmán et al. (2014). We mainly followed this methodology for calculating by-products, livestock produce and human diets, applying the estimates to the original data we had about the main produce, livestock composition and population of Les Oluges in the different points of time. However, the agroecosystem of Les Oluges had its own distinctive features, which have been represented as faithfully as the availability of data allowed.

The main raw data from which we started to build the energy profile of Les Oluges comes, first, from the land uses detailed in the text, to which we added their productivity, obtained from the local records and surveys or from provincial records. Table 6 shows the production of farmland in Les Oluges in physical terms.

Additionally, we estimated the NPP_{act} of the agroecosystem of Les Oluges considering not only the above-ground biomass, but also the below-ground biomass produced by the agroecosystem. Below-ground biomass was estimated following Guzmán et al. (2014) and refers to the roots of the trees and plants grown in the farmland. This is an important component of the phytomass produced, since it represents 48%, 35% and 20% of the NPP_{act} of Les Oluges in 1860, 1959 and 1999 respectively.

Table 6. Farmland production in Les Oluges in 1860, 1959 and 1999; according to our estimations.

FARMLAND PRODUCTION			**1860**	**1959**	**1999**
Yield (dry matter, kg/ha)	**Vegetable garden**	Main produce	825	922	3,873
		By-products	1,006	1,401	3,170
	Wheat (irrigated)	Main produce		2,064	
		By-products		3,654	
	Wheat	Main produce	550	1,032	2,536
		By-products	1,145	1,939	2,593
	Barley	Main produce	770	1,720	2,690

		By-products	1,603	3,220	2,804
	Rye	Main produce	467		
		By-products	973		
	Oat	Main produce		1,290	
		By-products		2,524	
	Fodder	Main produce			20,350
		By-products			
	Vine	Main produce	98	132	
		By-products	1,285	1,697	
	Olive	Main produce	77	320	1,167
		By-products	1,027	3,189	13,824
	Almond	Main produce		574	
		By-products		1,532	
Woodland, schrubland & pastureland (dry matter, kg/ha)		Woodland - timber & firewood	1,579	813	813
		Grass	1,002	1,002	1,002
		Acorns, mulch & others	73	73	
		Pinewood - timber & firewood		875	
		Riparian woods - timber &firewood		162	

The first adjustment we had to do in order to reflect the local specificities of Les Oluges involves the estimation of fallow land, which was traditionally widespread in Les Oluges. The historical records consulted, such as the *cartilla evaluatoria*, state that cropland sown with cereal was left uncultivated every other year. Therefore, we maintained half of the cereal cropland (for monoculture and associated crops) as fallow in our model for 1860. For 1959 we obtained local information by inquiry. Fallow was practiced every other year in most of the cereal cropland, except for the plots closer to the river, which were left fallow once every five years.

Secondly we had to estimate the amount and size of *formiguers* used in Les Oluges in 1860. We took as a reference the data available for a nearby village, Balaguer, and obtained a mean of 209 *formiguers* per hectare used in vegetable gardens and 102 *formiguers* per hectare in cereal cropland. Each *formiguer* would have been built with 20 kg of wood from woodland. According to the *cartilla evaluatoria* of Les Oluges, these were the only lands where *formiguers* were built. However, given the scarcity of manure that the historical records acknowledge for the Segarra County, and that in vineyard areas it was common to build *formiguers* with the pruned branches from the vines, we also added *formiguers* to the hectares were cereals and vineyard where intercropped.

The scarcity of manure and the widespread use of fallow were connected in Les Oluges. Scarcity of manure led to the need to keep cropland fallow in alternate years, but only the fallow land of monocultures was available for pasture since where cereals were sown between the vines, the strips left fallow could not be grazed because livestock could damage the vines. Thus livestock feeding required resources from the woodland to satisfy its needs, but this also meant that in 1860 a greater amount of manure was lost when animals were grazing.

For calculating the feed distribution among the livestock we followed these steps. For the energy balances of 1860 and 1959, first we calculated the feed available for livestock feeding, both from grains as barley, and from by-products, domestic residues and pastureland. Then we distributed it taking into consideration the suitability for each animal and the relevance of the animal for the sustenance and provision of the agroecosystem. For 1999, we did the same, but in this case we also include the feed imported from abroad and we included the embodied energy of this feed. Thus, in 1860 in order to fulfil the nutritional needs of the livestock, it was necessary to resort to woodland resources.

Grazing and *formiguers* are included in the resources extracted from woodland in 1860, but the total extraction of wood from the woodland was estimated using the data available for the nearby village of Balaguer. For 1959 and 1999 we used provincial data for the estimation of woodland biomass production and resources extracted from it.

When the agroecosystem of Les Oluges has been transformed into and industrial farm system, many local farming specificities have tended to disappear. Cropland was fertilised mainly with manure and synthetic fertilisers. The amount of manure available has been estimated according to the composition and management of the livestock-barnyard fund component of the agroecosystem. The information about the use of mineral fertilisers was obtained from local surveys that gave us the dose of synthetic fertilisers applied per hectare. By accounting a nutrient balance of the agroecosystem we obtained the total amount of synthetic fertilisers applied and the number of hectares fertilised (Table 7). For the nutrient balance we took into consideration the traditional cultural uses of cropland fertilisation–i.e. which crops were prioritised for fertilisation and which crops were seldom fertilised—and, for 1999, the limit set by the legislation which establishes a maximum of 170kg of nitrogen per hectare (Diari Oficial de la Generalitat de Catalunya DOGC, 2009).

Table 7. Manure and synthetic fertilisers applied in Les Oluges in 1860, 1959 and 1999; according to our estimations.

	Total kg			**Total hectares fertilised**			**Kg/ha**		
	1860	**1959**	**1999**	**1860**	**1959**	**1999**	**1860**	**1959**	**1999**
Manure (fresh matter)	920,947	1,540,252	35,562,160	165	269	791	5,580	5,719	44,979
Synthetic fertilisers		155,590	4,039,000		389	696		400	5,805

Finally, in 1999 we had to estimate the flux that we considered waste. In our case, it includes only the burned biomass of pruning. The surplus of straw available after satisfying its possible uses inside the agroecosystem (livestock feeding and bedding), has been considered FP. In 1999 the surplus of straw was 43% of the FP. Including this by-product as waste would have increased the volume of this flow more than twelve times and the FEROI would have fall to 0.28.

Chapter 3: Belowground and aboveground sustainability: Historical management change in a Mediterranean agroecosystem (Les Oluges, Spain, 1860-1959-1999)[5][6]

Abstract

This chapter studies the historical evolution of the farming practices in a semi-arid Mediterranean village (Les Oluges, Catalonia). We analyse the agroecosystem from a sociometabolic perspective at three different points in time (c.1860, 1959 and 1999), focusing on the estimation of the nutrient balances and connecting the assessment of the belowground sustainability with the aboveground dimension of agroecosystem management. Nutrient balances at the municipal scale were more equilibrated in 1860 and 1959 (with nutrient balances between -6 and 1 kg/ha) than in 1999 (with nutrient surpluses over 86 kg/ha), but at the crop system scale nutrient deficits existed at all the points in time. The discussion reflects the complexity of sustainable farming management assessing the efficiency, accomplishment and durability of soil fertility management, and concludes highlighting the unsustainability of industrialized agriculture and the value of integrated management of agroecosystems to improve agricultural sustainability.

1. *Introduction*

Mediterranean ecosystems have been managed by humans over millennia transforming and adapting their societies and the environment in a process of coevolution in which agriculture played an important role (Agnoletti & Emanueli, 2016; Blondel, 2006). Agricultural systems are shaped by biophysical and socioeconomic factors, which determine the adoption of different management practices. Since the spread of the Green Revolution throughout the second half of the 20th century, Mediterranean agroecosystems

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This work has been sent to the journal *Human Ecology* with me as corresponding author, and is in review process. I carried out the estimation of the nutrient balances, developed the analysis and wrote this work. José Ramón Olarieta was an important help providing me his advice as expert on soil sciences; him, together with Enric Tello, contributed in the guidance of the discussion process.

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experienced a great transformation. Traditional agricultural practices were locally adapted and fundamentally depended on organic resources, while modern agricultural methods can be characterized by their use of technologies and industrial external inputs largely dependent on fossil fuels. This transformation has entailed a series of environmental problems that challenge the sustainability of industrialized agriculture. In order to overcome the flaws of modern agricultural management the study of traditional farm systems is gaining attention as a source of valuable knowledge for a sustainable design and management of current and future agroecosystems (Altieri 2004; Eichhorn et al. 2006; Plieninger, Höchtl, and Spek 2006; Bignal and McCracken 2000; Barthel, Crumley, and Svedin 2013; Martin et al. 2010).

This work analyses the historical transition of the agroecosystem of Les Oluges, a small village in Lleida province (Catalonia, Spain), from traditional organic farming in the mid-19th century to a fully industrialized agricultural system in 1999. The analysis is grounded on the perspective of Social Metabolism, focusing on the material dimension of the exchange of energy and materials between society and the environment, and acknowledging that this exchange is mediated by culture (González de Molina & Toledo, 2014). Furthermore, the analysis of the agrarian metabolism of Les Oluges follows an agroecological approach considering that the flows of energy, water, and the cycling of nutrients are the most fundamental processes in agroecosystems, and human intervention is a key determinant of the functioning of these processes that distinguishes them from wild ecosystems (Stephen R. Gliessman, 2015). Farmers maintain the productive capacity of the agroecosystem by a continuous investment of external energy through their labour, material inputs and information, and by managing the resources available to replenish the nutrients extracted through harvest. Thus, the sustainability of an agroecosystem can be assessed by looking at how the different human management practices affect the flows of energy carriers and the cycling of nutrients that play a vital role in the reproduction of their renewable living funds (i.e. farmland, livestock-barnyard, farm-associated biodiversity, and farming community). Aboveground, the flow of energy has to keep some level of efficiency in terms of the energy needed to produce a unit of energy output to be sustainable in the long run (Tello et al. 2016), and the rate of extraction of resources cannot exceed the rate of regeneration of the funds. Belowground, a sustainable cycling of soil nutrients must also show an equilibrium between inputs and outputs. This will be assessed as the efficiency of the fertilization practices. Sustained deficits in the long term can involve soil nutrient mining and lead to a reduction of cropland fertility and productivity. Conversely, surpluses of nutrients can also create a loss of productivity and/or pollution problems. Ultimately, these imbalances can damage soil fertility, although many other processes and elements may affect it (García-Ruiz et al. 2012). There are several conditions that affect belowground sustainability beyond nutrient cycling (Neary, Klopatek, DeBano, & Ffolliott, 1999), such as soil physical characteristics, nutrient and water storage capacity, organic matter content and belowground biodiversity. Even though the historical resources available do not allow us to develop an in depth analysis of all of these conditions, we will provide an approximation to these issues by assessing the accomplishment of the fertilization practices. Finally, the assessment of belowground sustainability considers also the durability of the management practices regarding the renewability of the fertilizing sources employed.

2. *Methodology*

2.1. Nutrient balances

We calculate the nutrient balances for the three main macronutrients: nitrogen (N), phosphorus (P) and potassium (K). The methodology employed is based on previous studies for various Mediterranean agroecosystems at different scales (Galán del Castillo, 2015; Garcia-Ruiz, González de Molina, Guzmán, Soto, & Infante-Amate, 2012; Garrabou Segura & González de Molina, 2010). We consider the following flows of nutrients (see Methodological Annex):

-Human outputs: crops extraction (main produce and by-products)

-Human inputs: seeds, irrigation, buried biomass, manure (which includes humanure in 1860 and 1959), burnt biomass (*formiguers*[7]), and mineral and synthetic fertilizers.

-Natural outputs: gaseous losses of N and leaching.

-Natural inputs: atmospheric deposition, and symbiotic and non-symbiotic N fixation.

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[7] A *formiguer* was a heap of shrubs and small tree branches that was burnt under a soil cover in the cropland. Then, the ashes and charcoal were spread and buried into the soil.

Nutrient balances are a useful but limited tool for assessing the maintenance of soil fertility through agricultural management (Öborn et al., 2003; Oenema, Kros, & De Vries, 2003). First, nutrient balances do not cover all the physical and biological processes involved in the complex phenomenon of soil fertility. Some important conditions and characteristics of soils are left aside, such as soil rootable depth, texture and structure, cation exchange capacity, pH, salinity, organic matter and soil biota. A second limitation of the nutrient balances (shared with the reconstruction of the energy balances) is that it is not possible to obtain all the necessary local or on-site data, especially for their historical reconstruction. However, the balances of N, P and K presented in this work contain the most relevant fluxes of these nutrients, and the lack of data has been offset using available information from similar nearby agroecosystems and from modern studies that consider similar ecological conditions. Even though the results need to be interpreted with caution, they still offer an important insight into the long-term evolution of the agroecosystem sustainability.

The nutrient balances of Les Oluges have been calculated at two different scales. Aggregated results at municipal scale give an account of the total capacity of the agroecosystem for the replenishment of nutrients extracted within this boundary. In this respect it is important to acknowledge two limitations of this analysis. Firstly, given the lack of information about the flows of nutrients into and out of Les Oluges, we have assumed that the cycling of nutrients is confined to the administrative limits of the *municipio*[8], even though this was probably not the case in the past and is certainly not so in the present. Secondly, the data available for some flows of nutrients cannot be extrapolated to the municipal scale. We have dealt with these limitations specially for the estimating the flows of nutrients corresponding to manure and soil erosion, as explained in the next section.

Furthermore, a positive result at the municipal scale does not mean that soil nutrients are being replenished for all the land uses and particular plots. To complement this perspective, the nutrient balances for each type of crop system have been estimated. This approach allows us to appreciate the different management practices that might have been employed on each crop system and their capacity to sustain soil fertility.

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[8] A *municipio* (municipality or township) is an administrative unit composed by the built village centre and the surrounding rural areas of cropland, woodland and pastureland with some scattered farms or isolated buildings linked by a network of roads and paths.

2.2. Estimation of the main flows of nutrients

The structure of the agroecosystem was built using different historical records. Land-use registers and cadastres of the *municipio* provided cropland composition and the distribution of farmland among cropland, woodland, pastureland and urban uses. Additionally, information obtained from cattle census and local population registers determined the sizes of the livestock-barnyard complex and the farming community. The flows of nutrients were calculated from the structure of the agroecosystem.

Crop extractions was estimated multiplying the yields obtained according to local agricultural surveys by the nutrient contents of each crop according to Soroa (1953), Fernández-Escobar et al. (2015) and Galán del Castillo (2015). From these crop extractions, the amounts of nutrients reintroduced on cropland as seeds and buried biomass (stubble and vine pruning) were estimated.

The calculation of the volume of water used for irrigation was based on Vicedo i Rius et al. (1999) considering the different yields from rainfed and irrigated yields of wheat in Les Oluges. The resulting volume of water used for irrigation was 1900 m^3/ha in wheat and olive groves, and 3300 m^3/ha in vegetable gardens. The concentrations in N, P and K of the water used were obtained from Galan del Castillo (2015).

The availability of manure was estimated from the livestock-barnyard composition, excluding the losses during grazing and including animal beds. Additionally, manure in 1860 and 1959 includes human excreta. The total nutrients available for fertilization from manure exclude also the losses during composting and storage of the heap. The local sources available for 1860 and 1959 (JCA, 1890; Soroa, 1953) provided the information about the distribution of manure among crop systems and the doses applied. For 1999, manure was applied up to the maximum legal dose[9]: 170, 75, and 130 kg of N ha^{-1} for cereals, almond trees, and irrigated olive groves respectively. Given the large availability of manure in 1999, it was possible that flows of manure between the *municipio* of Les Oluges and nearby territories existed. It was not possible to obtain data for 1999, but current data revealed that the amount of local hectares fertilized with external manure is similar to the amount of external hectares fertilised with local manure (20% of cropland

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[9] http://agricultura.gencat.cat/web/.content/07-ramaderia/dejeccions-ramaderes-fertilitzants-nitrogenats/enllacos-documents/fitxers-binaris/annex_3_dosis_maximes.pdf

approximately). These fluxes would thus cancel each other and we excluded these flows from our balances.

For estimating the flows of nutrients from *formiguers* we followed Les Oluges agricultural survey (*cartilla evaluatoria*) of 1883, which indicated that they were built only in vegetable gardens and cereals. We estimated their size and the number of *formiguers* built in each crop system on the basis of their monetary value. The effectiveness of *formiguers* for the management of soil fertility has long been debated (Roxas Clemente, 1808). Modern experiments show that, further from the direct input of N, P and K in charcoal and ashes, the mineralization of organic matter caused by the heat of the formiguer produced a flush of plant available P, while the loss of mineral N during burning was compensated in the short term by an increase in the mineralization of organic N afterwards. Additionally, *formiguers* helped to reduce weeds and pests, and aided in ‘loosening’ the soil (Mestre & Mestres, 1949; José Ramón Olarieta et al., 2011). In this work, the nutrient contribution of each *formiguer* was estimated following the results from Olarieta et al. (2011).

The information about the use of industrial fertilisers was obtained from local informants[10]. According to these, the doses applied in the mid-20th century were 1 kg of guano per kg of seeds, and 1 kg of ammonium nitrate per kg of seeds, and they were only applied on cereals. In 1999, the doses applied were 7,000 kg/ha of a compound fertilizer 2/2/1 (which provides 140 kg of N, 140 kg of P and 70 kg of K) and 270 kg/ha of “spring nitrate”, which has been considered to be calcium ammonium nitrate with a 27% content of N. However, the total N applied according to the doses in 1999 (213 kg of N ha^{-1}) is above the legal allowed (120 kg of N ha^{-1}). Since both hypotheses resulted in large surpluses of nutrients, the results showed in this work correspond to the mean between them.

The distribution of manure and industrial fertilizers in 1860 and 1959 has been estimated considering the different soil qualities recorded in the sources consulted. According to the historical records of 1860, the distribution of crops and fertilizing resources were linked to the quality of the soil: best quality soil was sown with wheat and received greater fertilization, while medium and lowest quality soils were sown with barley and rye

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[10] We would like to thank Xavier Mestre, Josep Maria Llenes and Vicent Torres for their information about the agricultural managements in 1959 and 1999.

respectively and received lower doses of fertilization. In the same vein, for 1959 we have considered that wheat was fertilized with mineral fertilizers and was left fallow one every five years, while barley and oat only received manure and were left fallow every other year. In 1999 there is no distinction among soil qualities, and the distribution of fertilizing sources was made considering the records of fertilized surfaces, which indicate that 10% of the almond trees were fertilized, and irrigated olives received manure. For cereals, we distributed first the manure, until the maximum legal dose, and once all the manure was applied, we considered the remaining hectares fertilized with industrial fertilizers.

The flows of other inputs and outputs have been estimated following different sources that provided data for ecological conditions similar to our agroecosystem (Bosch Serra, Iglesias Fernández, Amat Bové, & Boixadera Llobet, 2007; Galán del Castillo, 2015; Harris, 1988; Peoples et al., 2016).

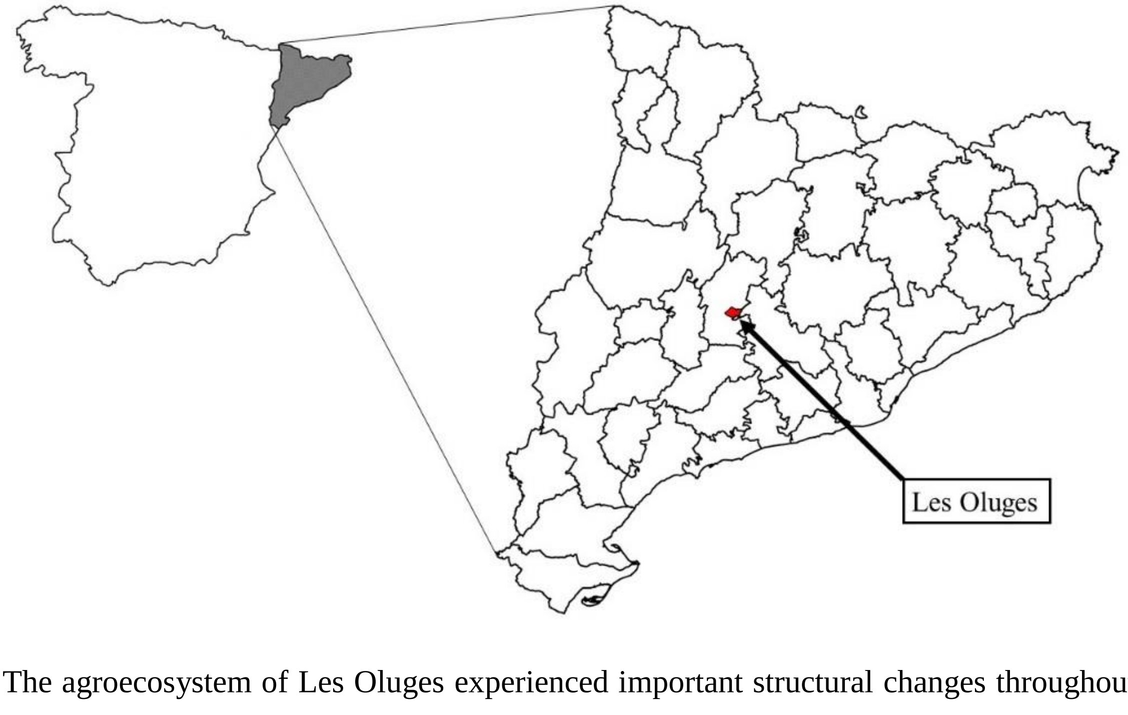
Fallow was also a widespread practice for managing soil fertility in traditional agriculture, especially in arid and semi-arid climates (Stephen R. Gliessman, 2015; Oliver, Robertson, & Weeks, 2010). However, fallow is not a fertilizing method in terms of nutrient replenishment, but a way of managing soil fertility by increasing the water stored on the soil, and by helping to control weeds, diseases and pests (Oliver et al., 2010; Shiel, 2006). According to the historical sources, in 1860 cereal cropland in Les Oluges needed to be left fallow every other year, and in 1959 this need was reduced to one every five years but only in the soils of best quality. In order to show the relevance of this management we have differentiated the input of nutrients through the natural processes of deposition and non-symbiotic N fixation that occur in fallow land (included under the label 'fallow' in the nutrient balances at the crop system scale) and in sown cropland.

Finally, we have not included the nutrient losses caused by soil erosion because, at the aggregated scale, the soil erosion that affected mainly platforms at the top of the hills, would be cancelled by the deposit of these sediments in the valley floors and terraced slopes. At the crop system scale, it was not possible to make proper estimations of the distribution of land uses and crop systems for all the points in time studied, as would be needed to determine soil erosion and formation. However, in this respect it is important to highlight the existence of terraces, an ancient form of soil conditioning aimed at improving cropland fertility, but not at the replenishment of nutrients. Dry-stone terraces were an important part of the traditional biocultural landscapes (Agnoletti & Emanueli, 2016). In Les Oluges, they were originally built not only for flattening slopes and increasing the land suitable for cultivation, but also as way of reducing soil erosion and managing surface runoff (Olarieta and Padró 2016). The construction and maintenance of terraced systems, linked to traditional management practices and knowledge (Sandor, 2006), has been abandoned to a great extent in recent times.

3. *The structure of Les Oluges agroecosystem and its historical transformation*

Les Oluges is a small village from La Segarra County, in Lleida (Catalonia) (Figure 6). It is located on the upper valley of the Sió River, at 490-650 m.a.s.l. The climate is dry continental Mediterranean, with cold and foggy winters and hot and dry summers. Average annual rainfall is below 500 mm, and the period of water stress runs from April to October (Ramon Garrabou et al., 1999). The capacity for irrigation was severely limited by the scarce volume of water of the Siò and Riera de Vergós rivers. These semi-arid climate conditions limited crop yields and endangered harvests through recurrent draughts and frosts.

Figure 6. Map of Spain and Catalonia showing the location of Les Oluges. Source: our own.



The agroecosystem of Les Oluges experienced important structural changes throughout the time span studied, as the size, composition, and interrelationships of its living funds were transformed. These changes can be outlined in three processes.

Table 8. Composition of the main agroecosystem funds of Les Oluges in 1860, 1959 and 1999. Source: Our own, from the sources detailed in the text.

Les Oluges - FUNDS				**1860**		**1959**		**1999**	
Farming community	Inhabitants			795		404		191	
	Annual Working Units[11]			102		181		35	
Farmland (hectares)	**Cropland**	Cereals	Sown	161	36%	515	58%	1,486	93%
			Fallow	161		399			
		Associated Crops	Sown	422	63%	427	36%		
			Fallow	141		139			
		Others		4	1%	93	6%	76	5%
		Fallow						28	2%
		Total		**888**	**47%**	**1,573**	**84%**	**1,591**	**84%**
	Pastureland			**156**	**8%**	**93**	**5%**	**0.2**	**0%**
	Woodland & scrubland			**831**	**44%**	**209**	**11%**	**302**	**16%**
Livestock	Horses			2		3			
	Mules			56		120			
	Donkeys			146		10			
	Cows & oxen			20				600	
	Swines			165		80		6,588	
	Sheeps & goats			325		310		500	
	Fowl and rabbits			790		2,550		369,026	
	LU500			**151**		**124**		**3,082**	

First, from 1860 to 1999 there was a process of cropland expansion, particularly intense from 1860 to 1959. Traditionally, cereals were the most widespread crop in Les Oluges, growing mainly wheat, barley, and rye. However, from the second half of the 19th century the *Phylloxera* crisis in France created favourable market conditions that propelled vineyard expansion in Catalonia. This enlargement was carried out in Les Oluges by clearing woodland and using the traditional intercropping system in which cereals were grown between the widely-spaced rows of vines. The crop system that associated vines and cereals became the most abundant in 1860 (Table 8) (with 96% of the cropland under associated crops corresponding to vines and cereals, and 4% to olive trees and cereals). In 1894 the *Phylloxera* plague reached the Segarra County ending the vineyard boom (JCA, 1911), and the agroecosystem returned toward cereal production, substituting rye with oat. The presence of vines decreased (only 25% of associated crops corresponded to

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[11] http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Annual_work_unit_(AWU)

vines and cereals in 1959), but the alley crop association system was maintained with the introduction of olive and almond trees (Figure 7) (Pujadas i Rúbies et al., 1980). In 1999, grain monocultures took up most of the cropland, with barley being grown in 80% of the area of cereals.

Figure 7. Aerial pictures of Les Oluges in 1956. The image on the top shows a general overview of the village and the surrounding cropland; the bottom image shows the detail of the intercropping system. Source: Orthophotos of Catalonia in 1956-57 from the Institut Cartogràfic i Geològic de Catalunya (ICGC), under licence CC BY-NC-SA 4.0.

In addition to cropland enlargement there was also an increase in cropland productivity throughout the whole period (Table 9). This process was twofold: the introduction of new seeds and industrial fertilizers from the mid-20th century allowed, on the one hand, to increase yields and, on the other hand, reduced the need for fallow and therefore increased the area of cereals sown.

Table 9. Mean yields of the crops grown in Les Oluges in 1860, 1959 and 1999. Source: Our own, from the sources detailed in the text.

CROP YIELDS (kg fresh matter ha^{-1})		1860	1959	1999
Vegetable gardens	Main produce	8,675	9,392	26,078
	By-products	7,881	5,582	17,079
Cereals	Main produce	693	1,567	3,039
	By-products	1,442	2,855	3,138
Vines	Main produce	693	780	
	By-products	2,379	3,243	
Olive trees	Main produce	113	320	808
	By-products	1,195	4,520	14,037
Almonds	Main produce		600	467
	By-products		1,795	1,795
Fodder				18,178

Secondly, the agroecosystem of Les Oluges experienced a continuous process of depopulation from 1860 to 1999. The farming community in 1999 was only one quarter of that in 1860. The agricultural crisis after the *Phylloxera* plague boosted agricultural migration to industrial centres and cities, and in the first half of the 20th century the introduction of machinery, mineral fertilizers and new seeds increased labour productivity and reduced the need of agricultural workers.

Finally, the process of modernization of the agroecosystem affected also the composition and volume of the livestock-barnyard fund. From 1860 to 1959, livestock density decreased 18% (Table 8) because of the lower agrarian population and the introduction of new machinery that reduced the need for animal draft force. The greater availability of feeding resources allowed to substitute mules for donkeys and the availability of manure increased (Table 10) due to a reduced need for pasture (Díez et al., 2018). From 1959 to 1999 livestock density multiplied by 25 and animal husbandry was also transformed. While traditional livestock management was integrated in farmland, with animals feeding from by-products, domestic residues and grazing in less productive soils, under industrial management livestock was kept on feedlots and depended on feed imports.

Table 10. Manure availability and distribution among crop systems in Les Oluges in 1860, 1959 and 1999. Source: Our own, from the sources detailed in the text.

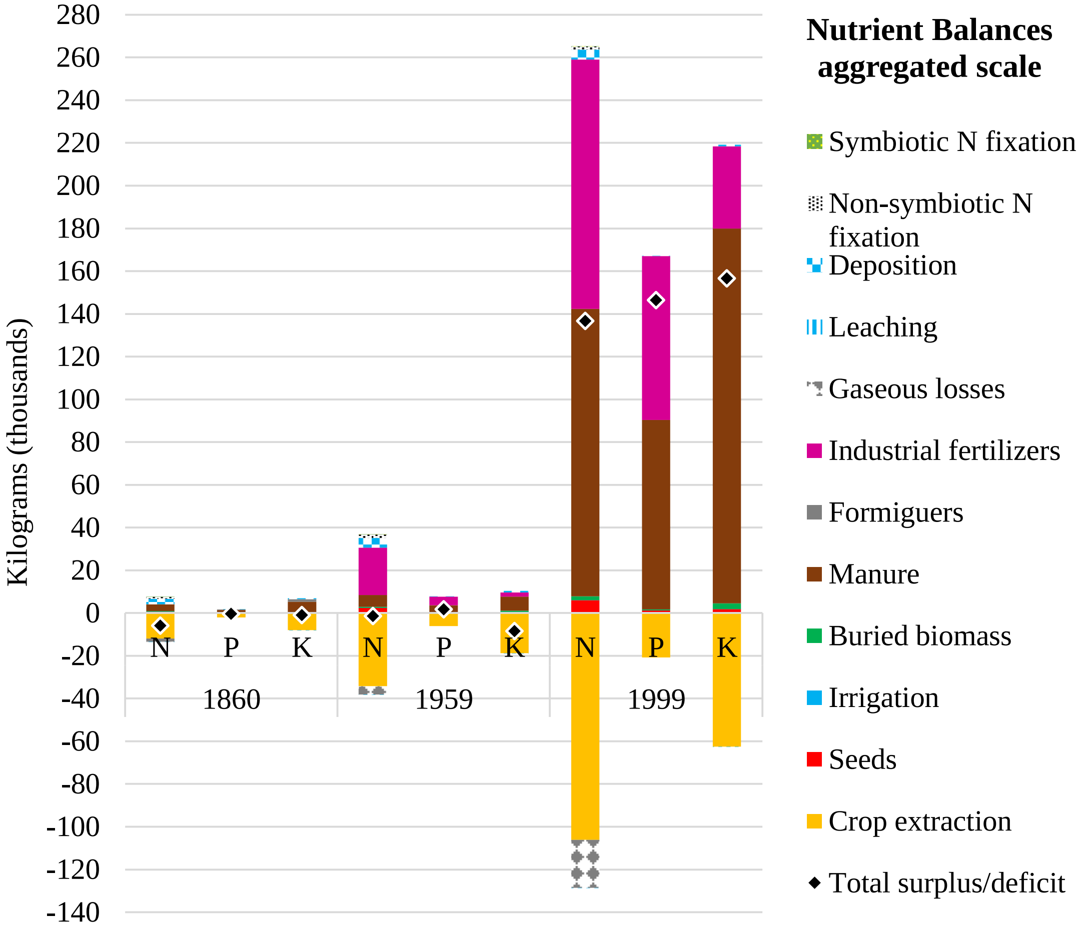
MANURE		**1860**	**1959**	**1999**
Total available (kg fresh matter)		1,242,572	1,540,252	35,562,160
Mean dose of manure applied on cropland (kg fresh matter ha^{-1})	Vegetable gardens	10,184	10,000	20,000
	Cereals	1,567	5,643	44,965
	Almonds			19,841
	Irrigated olive trees			34,391

4. Nutrient balance results

4.1. Aggregated scale

Figure 8 shows the remarkable increase in the flows of nutrients in Les Oluges especially from 1959 to 1999. The volume of nutrients extracted rose with cropland enlargement and increased cropland productivity, but the application of manure and industrial fertilizers made it possible to offset that greater extraction. However, while in 1860 and 1959 the input and output of nutrients were nearly balanced, in 1999 the volume of nutrients introduced in cropland was larger than the nutrients extracted, thus leading to a great surplus in the nutrient balances (Table 11).

Figure 8. Nutrient balances of Les Oluges in 1860, 1959 and 1999 at the aggregated scale. Source: Our own, from the sources detailed in the text.



In 1860, the main input of nutrients came from manure, followed by atmospheric deposition (which respectively provided 48% and 10% of the nutrients extracted). However, in terms of area fertilized, *formiguers* were the most widespread management, since they were built in cereal monocultures and in the intercropping system that combined vines and cereals. *Formiguers* played an important role as input of nutrients: they provided 15% of the P and K extracted, but they had an initially negative impact on N increasing by 13% the human extraction of this nutrient.

Table 11. Detail of the flows of nutrients and the surplus/deficit of the nutrient balances of Les Oluges in 1860, 1959 and 1999 at aggregated scale. The hectares refer to the total surface on which this flow of nutrients occur. The figures of N, P and K refer to the mean kg/ha of each flow. Source: Our own, from the sources detailed in the text.

Detail of the nutrient balances at the aggregated scale	**1860**				**1959**				**1999**			
	ha	**N**	**P**	**K**	**ha**	**N**	**P**	**K**	**ha**	**N**	**P**	**K**
Crop extraction	888	-13.40	-2.35	-8.98	1573	-21.77	-3.90	-12.02	1591	-66.78	-13.05	-39.38
Seeds	306	2.04	0.38	0.46	929	2.57	0.42	0.51	1492	4.03	0.86	1.23
Irrigation	4	2.90	0.07	1.83	8	2.41	0.05	1.52	4	2.64	0.06	1.66
Buried biomass	422	0.70	0.07	0.91	941	0.48	0.10	0.62	1487	1.24	0.23	1.83
Manure	165	19.01	7.20	29.14	269	20.82	11.50	24.39	795	169.10	111.59	220.70
Formiguers	570	-2.72	0.53	2.04								
Industrial fertilizers					389	56.75	10.47	5.23	701	166.45	109.46	54.73
Gaseous losses	4	-8.5			658	-6.03			1496	-14.96		
Leaching	4	-7.5	0	-3.5	8	-7.5	0	-3.5	4	-7.5	0	-3.5
Deposition	888	2.90	0.07	0.50	1573	2.90	0.07	0.50	1591	2.90	0.07	0.50
Non-symbiotic N fixation	888	1.00			1573	1.00			1591	1.00		
Symbiotic N fixation	4	22.41			5	22.41			5	13.09		
Total surplus/deficit		**-7 (±0)**	**0 (±0)**	**-1 (±0)**		**-1 (±0)**	**1 (±0)**	**-5 (±0)**		**86 (±21)**	**92 (±14)**	**98 (±7)**

In 1959 the nutrient balances improved for N and P, but worsened for K. Again, the surpluses and deficits are not large enough to consider them determinant. The agroecosystem was functioning in a relative equilibrium of nutrient cycling, although it must be noted that the area and productivity of cropland were much higher in 1959 than in 1860 (Table 8 andTable 9). The area fertilized with manure increased 63%, providing an input of nutrients per hectare similar to that of 1860. However, it was the introduction of mineral fertilizers which played a key role in the increased capacity of the agroecosystem for sustaining the higher nutrient extraction, even though this was achieved at the expense of the alien territories from where the guano and ammonium nitrate were extracted (Cushman, 2013). Furthermore, the availability of these new fertilizing source enabled the abandonment of the use of *formiguers*, which required a large investment of labour.

Finally, the relative balance of inputs and outputs of nutrients changed in 1999. The extraction of nutrients increased more than three-fold between 1959 and 1999, while the input of nutrients multiplied by a factor of thirteen. Not only manure was widely available because of the greater livestock density, but the amount of industrial fertilizers applied also increased. Compared with 1959, the area fertilized with industrial fertilizers increased 80%, with a mean input of nutrients almost eight times larger. Along with the greater input of nutrients, losses also rose. However, the results obtained at the aggregated scale show large surplus in the balances of the three soil macronutrients.

4.2.Crop system scale

The results of the nutrient balances for each crop system in 1860, 1959 and 1999 are shown in Table 12. When we look at the crop scale the distribution of the deficits and surpluses of nutrients can be qualified according to the management practices carried out on each crop system, which is related to the different value or importance given to each crop in the socioeconomic and cultural context. At the three points in time studied most of the crop systems were actually experiencing a deficit of nutrients. Only cereal monocultures achieved positive nutrient balances, and intercropping system and woody crops monocultures tended to have nutrient deficits.

Given the large diversity of crop systems in Les Oluges, especially until the mid-20th century, we will focus the analysis on the most widespread crop systems: cereal monocultures, and alley-cropping of vines and cereals in 1860 and 1959; and cereal monocultures and almond trees in 1999.

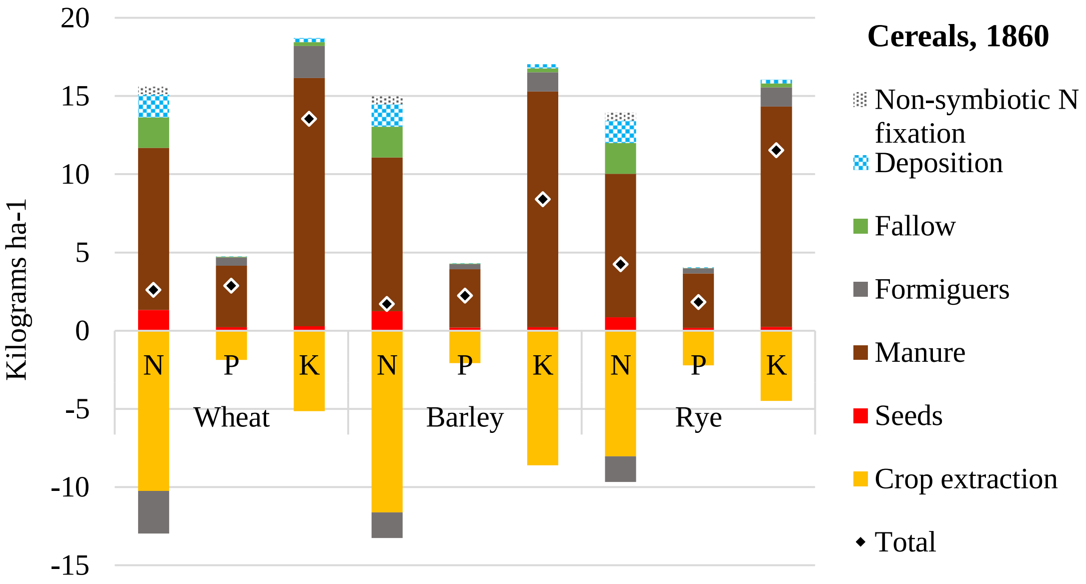
Table 12. Nutrient balances of the crop systems of Les Oluges in 1860, 1959 and 1999 (kg/ha). Source: Our own, from the sources detailed in the text.

Nutrient balances		**1860**				**1959**				**1999**			
Crop systems		**ha**	**N**	**P**	**K**	**ha**	**N**	**P**	**K**	**ha**	**N**	**P**	**K**
Vegetable gardens		4.28	-51.51	-13.92	-30.11	4.65	8.41	11.90	4.10	0.28	23.24	40.02	35.49
Cereals	Irrigated wheat					3.11	-21.62	-1.78	-29.46				
	Wheat	47.29	2.61	2.88	13.56	492.96	15.12	2.85	-6.47	301.39	87.95	98.44	107.91
	Barley	114.02	1.72	2.25	8.41	320.91	-11.81	1.66	-4.20	1185.04	93.96	98.21	103.92
	Rye	160.20	4.26	1.83	11.55								
	Oat					97.20	-8.58	2.78	1.96				
Fallow										28.22	3.90	0.07	0.50
Fodder										5.13	6.38	-1.06	-1.57
Olives (rainfed)		0.18	-3.21	-0.15	-0.02	6.31	-18.17	-0.27	-1.02	12.80	-62.76	-2.04	-4.50
Olives (irrigated)										3.80	-74.56	79.73	153.63
Vineyard						56.54	-11.06	-1.70	-10.96				
Almond trees						25.54	-20.10	-6.79	-7.81	53.87	-5.47	1.38	5.58
Vines & wheat		27.42	-18.45	-2.11	-9.96	117.06	2.53	0.62	-6.97				
Vines & barley		156.96	-16.03	-2.18	-11.18	21.65	-10.81	0.25	-6.44				
Vines & rye/oat		355.87	-10.12	-1.68	-6.43	5.28	-9.07	0.86	-3.14				
Olives & wheat		0.65	-4.38	-0.87	-2.14	17.90	3.75	1.34	-3.30				
Olives & barley		7.84	-4.03	-0.94	-3.77	25.29	-11.20	0.93	-2.71				
Olives & rye/oat		13.62	-1.50	-0.94	-1.56	5.34	-9.25	1.61	0.99				
Vines, olives & rye		0.15	-3.94	-1.35	-4.07								
Almonds & wheat						61.13	1.44	-0.86	-6.06				
Almonds & barley						56.71	-13.98	-1.20	-4.33				
Almonds & oat						10.59	-12.28	-0.51	-0.65				
Vine, almonds & wheat						77.66	-2.74	-1.20	-7.09				
Vine, almonds & barley						38.38	-13.25	-1.48	-6.68				
Olives, almonds & wheat						22.38	-2.78	-0.98	-4.69				
Olives, almonds & barley						36.08	-13.81	-1.28	-4.26				
Olives, almonds & oat						1.64	-12.38	-0.78	-1.53				
Vine, olives, almonds & wheat						58.47	-8.76	-2.09	-6.48				
Vine, olives, almonds & barley						9.90	-13.21	-2.21	-6.31				

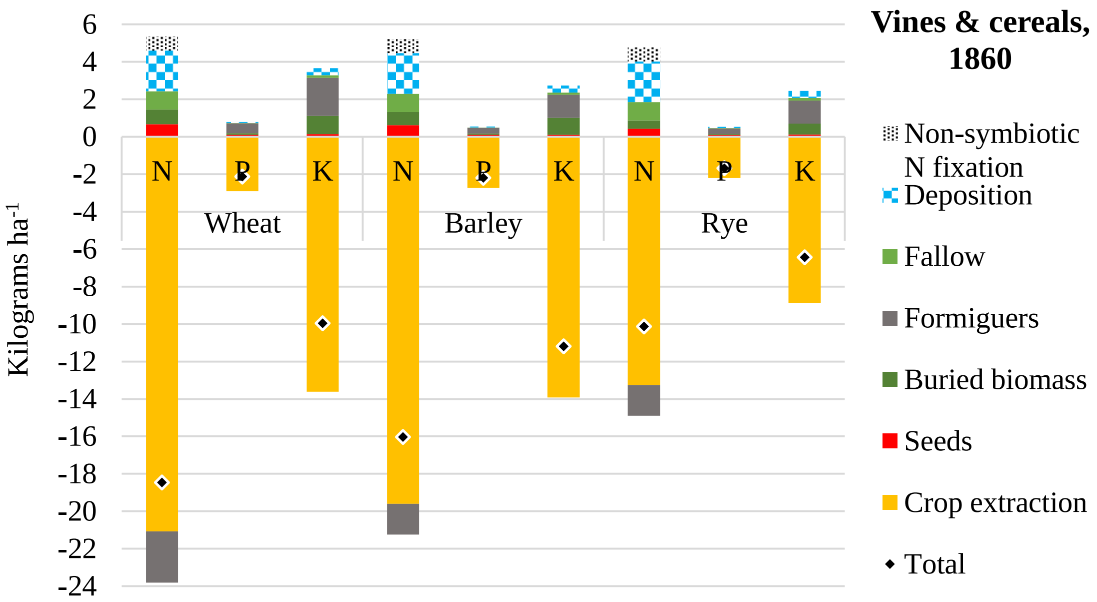
In 1860 only cereals grown as monocrop achieved a positive balance of nutrients. According to the historical records, given the scarcity of manure it was applied in vegetable gardens, and in cereal monocultures when supply was sufficient (Figure 9a). Additionally, wood from woodland was used to burn *formiguers* in the cereal land to supplement manure. These where the main inputs of nutrients in cereal monocultures, together with fallow, and constituted a net input of nutrients from woodland and pastureland into cereal cropland (except for the nutrients recycled from the by-products fed to animals and reintroduced as manure). However, fallow was the only technique that contributed a net input of nutrients (Figure 9b) as the other practices associated with the restoration of soil fertility were actually a recycling of the nutrients extracted through the by-products (*formiguers* in this crop system were built with vine pruning instead of wood from woodland). The intercropping of vines and cereals showed a negative balance of nutrients, but it must be highlighted that it was less pronounced in the case of vines and rye, which was the most widespread intercrop (Table 12).

Figure 9. Detail of the inputs and outputs of the main crop systems of Les Oluges in 1860. 9a) Composition of the nutrient balances of cereals; 9b) Composition of the nutrient balances of the intercropping of vines and cereals. Source: Our own, from the sources detailed in the text.

9a)



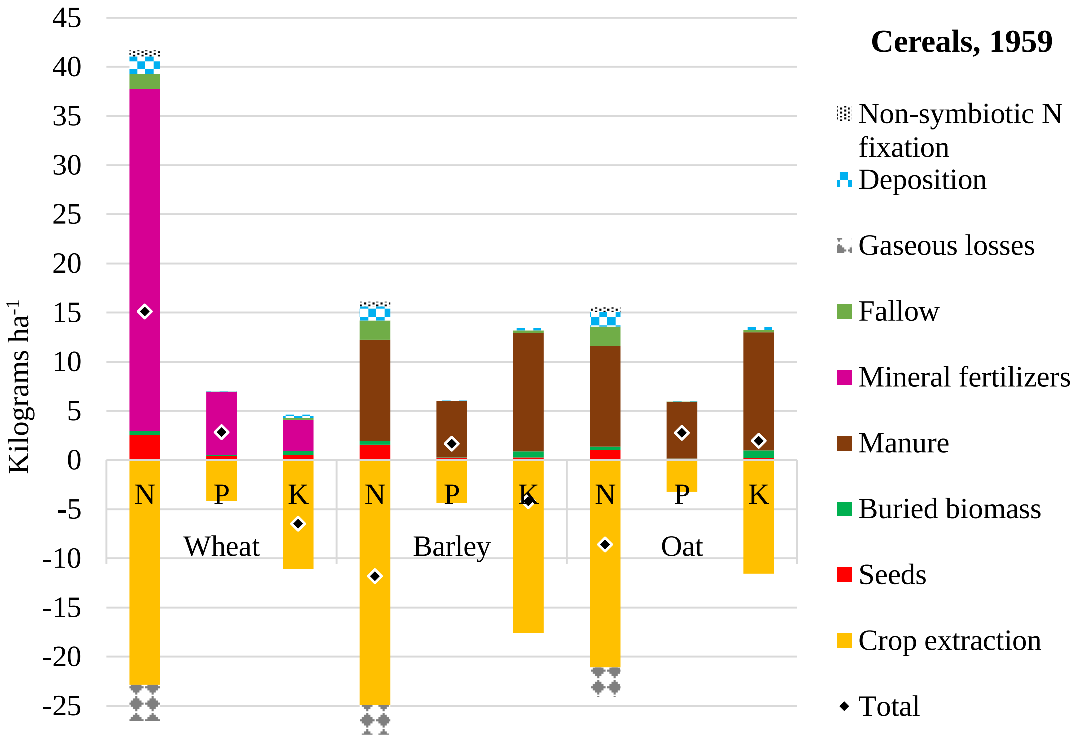
9b)



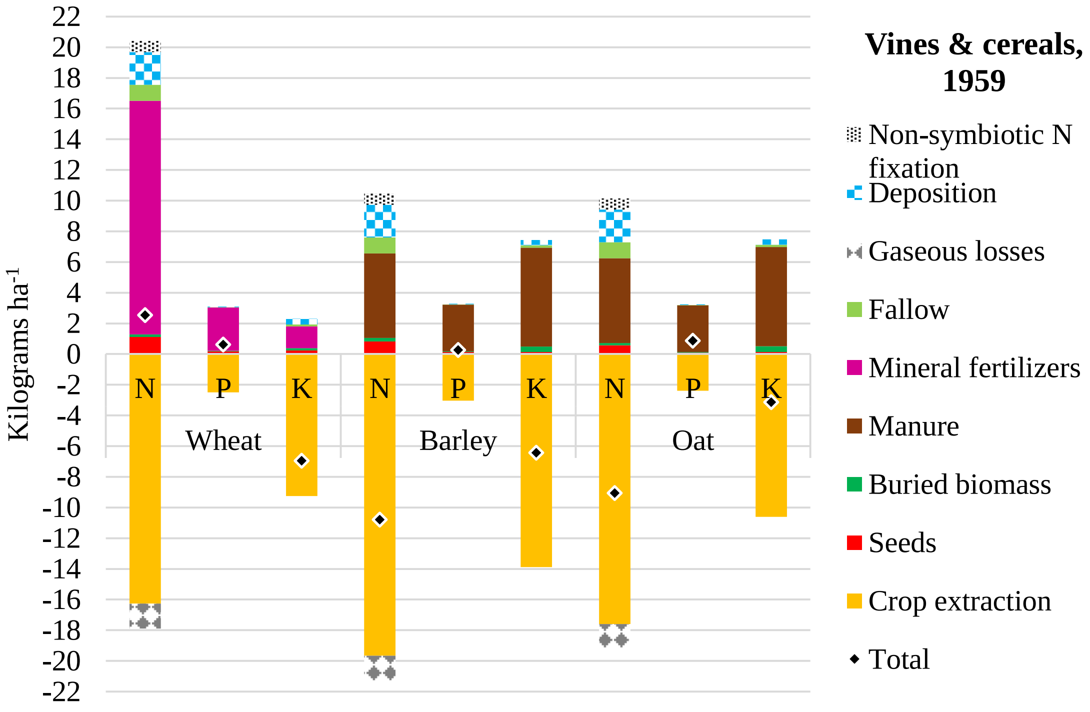
In 1959 the situation was more complex. Most crop systems had nutrient deficits, especially for N and K. The distribution of these deficits was determined to a great extent by the kind of fertilization applied on each type of crop. Taking this into consideration, our results show that those crop systems that received mineral fertilizers were more generally able to replenish the N extracted, though the application of manure provided a more balanced input of the three macronutrients (Figure 10).

Figure 10. Detail of the nutrient balances of the main crop systems of Les Oluges in 1959. 10a) Composition of the nutrient balances of rain-fed cereals; 10b) Composition of the nutrient balances of the intercropping of vines and cereals. Source: Our own, from the sources detailed in the text.

10a)



10b)

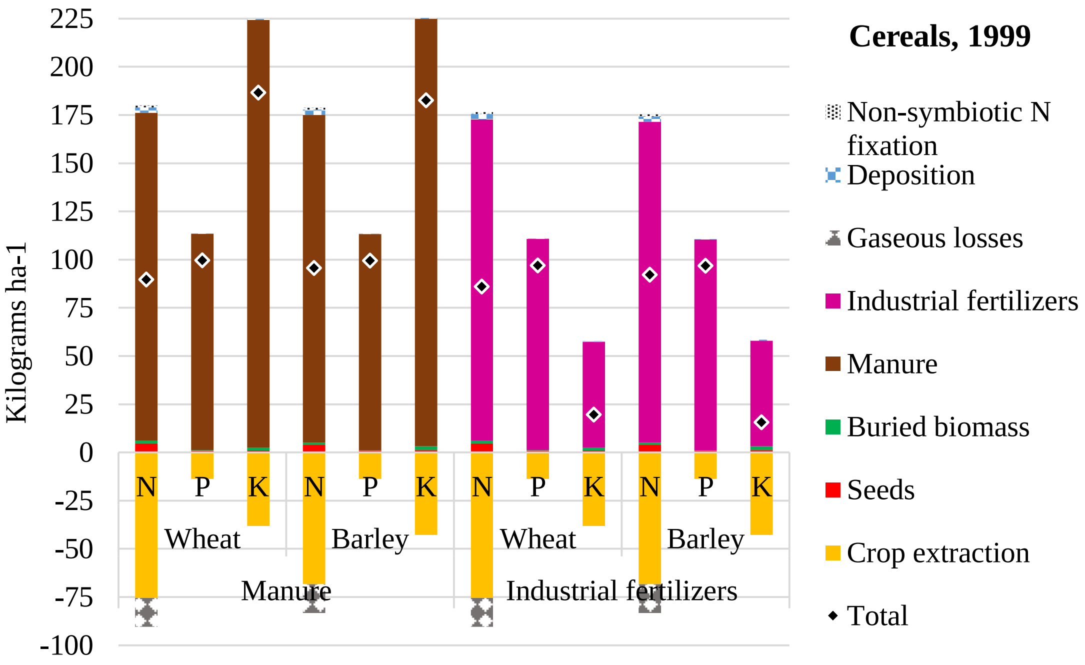


Given that there was a greater availability of fertilizers, all the crop systems which included cereals (as a single crop and in association with other crops) could receive either manure or mineral fertilizers. However, as the intercropping systems increased the number of species included, the surpluses of nutrients were reduced and deficits rose.

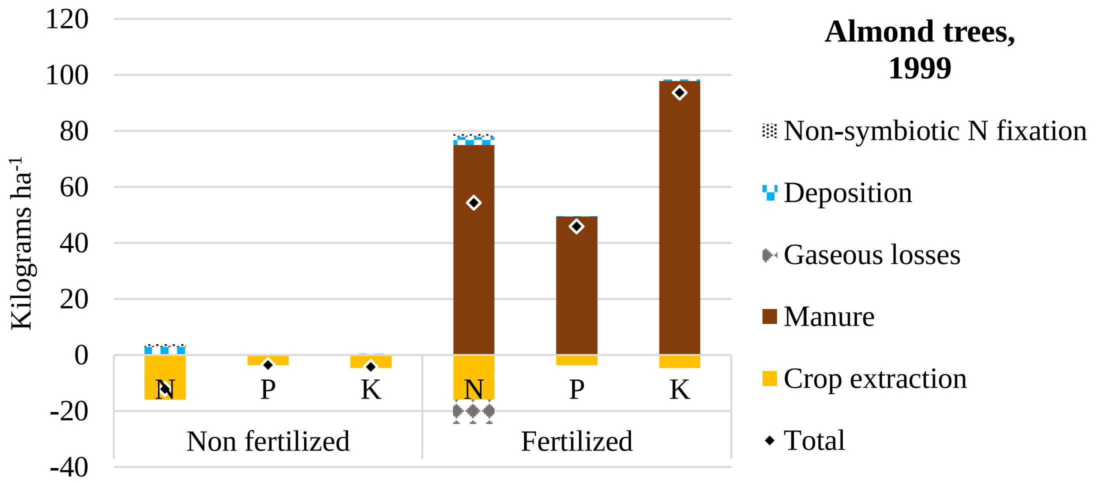
In 1999 the different management practices applied allow us to distinguish among woody crops and cereals, but there is no difference in the fertilization applied to wheat and barley.

Figure 11. Detail of the nutrient balances of the main crop systems of Les Oluges in 1999. 11a) Composition of the nutrient balances of cereals; 11b) Composition of the nutrient balances of almonds. Source: Our own, from the sources detailed in the text.

11a)



11b)



The availability of fertilizers escalated in 1999, but their distribution remained unequal (Table 12). Cereal monocultures, which covered 93% of cropland, obtained large surpluses of nutrients, either when fertilized with manure or with synthetic fertilizers (Figure 11a). Fallow was abandoned as a strategy for soil fertility management, and it became a way to obtain subsidies from the European Common Agricultural Policy (CAP). Woody crops received some fertilization with manure, but it was only applied in irrigated olive groves and in 10% of almond hectares. The almond fields fertilized with manure had a largely positive balance of nutrients (Figure 11b), whereas manure applied on irrigated olive trees (with the maximum dose legally allowed) could not offset a negative balance of N (Table 12).

5. *Discussion*

5.1. Changes in soil fertility management: efficiency, accomplishment and durability

The results obtained from the nutrient balances of Les Oluges in 1860, 1959 and 1999 are relevant to examine the sustainability of the different management practices of soil fertility applied in each period from a combined perspective that evaluates their efficiency, accomplishment and durability.

Efficiency is assessed considering the capacity of these practices for balancing the nutrients extracted. In this sense, the nutrient balances of 1860 and 1959 can be considered more efficient than those of 1999. The former were close to equilibrium, meaning that nutrients might have been replenished even though the fertilizing resources available at the aggregated scale were quite scarce. Additionally, most of the deficits and surpluses at the crop system level were not severe, which underlines the effort and ingenuity of farmers to sustain crop yields in a context of low availability of fertilizers that required a great investment of biomass recycling in order to reintroduce part of the nutrients extracted. On the contrary, the large surplus of nutrients in 1999 for some of the crop systems and at the aggregated scale reveals an excessive and inefficient use of fertilizers that could even damage cropland fertility in the long run.

Accomplishment of the soil fertility management can be qualitatively understood from an agroecological perspective as the capacity of the fertilization techniques to contribute not only to the cycling of nutrients, but also to some of the other elements that determine soil fertility. An in-depth analysis of these elements would go beyond our possibilities, but it is possible to approximate some of the effects of certain management practices. First, we can assess the effects on three interrelated elements: soil organic matter content, soil biodiversity, and water and nutrient storage capacity. Among the fertilizers applied in Les Oluges, manure and buried biomass are the most important sources of organic matter. They were used in all the time points studied, with similar relevance in 1860 and 1999 (being 68% and 62% of the total nutrient inputs respectively) but with lower relevance in 1959 (being 42% of the total nutrient inputs). Soil organic matter improves the capacity of the soil to retain water and nutrients, but also serves as food for soil biota, which performs multiple functions in soils and is of great importance for the sustainability and fertility of soils (Bardgett & Van Der Putten, 2014; Brussaard, de Ruiter, & Brown, 2007; Stephen R. Gliessman, 2015). Furthermore, belowground biodiversity is linked to aboveground biodiversity (De Deyn & Van Der Putten, 2005; Wardle et al., 2004), which we estimate was greater in 1860 and 1959, when the various intercrops may have increased biodiversity at the crop system scale. Conversely, soil biota can be negatively affected by pesticides, herbicides and industrial inorganic fertilizers (Thiele-Bruhn, Bloem, de Vries, Kalbitz, & Wagg, 2012). These are widely used in modern intensive agricultural systems, such as Les Oluges in 1999. Furthermore, pharmaceutical antibiotics used in intensive livestock farming, which are present in the manure applied in cropland, can also be detrimental for soil biodiversity. Finally, fallow and terraces were traditional management practices aimed to improve the nutrient and water storage capacity of soils in 1860 and 1959 that were vanishing in 1999. Thus, even though we cannot measure the effect of these practices in our historical analysis, it is possible to assert that the traditional practices employed in 1860 and 1959, when the agroecosystem was under an organic and mixed industrial-organic management, would have been better suited for the accomplishment of soil fertility than the industrial practices of 1999.

The durability of the soil fertility practices may be assessed considering the renewability or non-renewability of the fertilizers employed. In this respect, mineral and synthetic fertilizers obtained from finite natural resources and polluting industrial processes imply the unsustainability of the practices in 1959 and 1999. However, the renewability of fertilizing resources would also be endangered in 1860 when woodland was cleared for expanding cropland and by the extraction of biomass by grazing and to produce *formiguers*. Thus, in order to evaluate the durability of the management practices, we will connect the belowground and aboveground sustainability of the agroecosystem to complete our assessment.

5.2. Belowground and aboveground sustainability

The energy analysis of the farm system of Les Oluges (Díez et al., 2018) provides some insights on the aboveground dimension of the agroecosystem sustainability and emphasizes some of the results obtained from the belowground analysis.

First, the industrialized management of the agroecosystem in 1999 was not sustainable neither above- nor below-ground, despite its high productivity and the large availability of fertilizing resources. The energy efficiency of Les Oluges in 1999 was the lowest among the studied periods, as a result of the large increase of livestock density and the large dependence on external inputs that reduced and partially replaced the energy recirculated within the agroecosystem. In 1999 Les Oluges required two units of energy for each unit of energy produced (Díez et al. 2018), and introduced more than 4 units of macronutrients per unit of macronutrient output.

Secondly, the aboveground and belowground analyses emphasize the relevance of the integrated management of farmland funds usually found in organic farm systems (Gingrich, Haidvogl, Krausmann, Preis, & Garcia-Ruiz, 2015; Fridolin Krausmann, 2004; Tello, Garrabou, Cussó, Olarieta, & Galán, 2012) with livestock and biomass recycling playing a key role. Soil fertility practices in 1860 and 1959 were better able to balance nutrient cycling with a lower dependency on external inputs and, additionally they were better adapted to assess the multiple processes that affect soil fertility. The energy analysis of Les Oluges in 1860, and especially in 1959, revealed an agroecosystem that was able to combine biomass reuses and external inputs so that provision for human purposes and farm associated biodiversity (which is linked to the provision of ecological services) were reasonably balanced.

However, the sustainability of these traditional agroecosystem managements in 1860 and 1959 needs to be further qualified. The intensive use of woodland and the deforestation process in 1860 could not have continued indefinitely, and would have ultimately compromised the sustainability of the agroecosystem. The arrival of the *Phylloxera* plague and the introduction of mineral fertilizers and modern machinery changed the socioeconomic context and technological possibilities of Les Oluges. Mineral fertilizers reduced the local land cost of the agroecosystem sustainability (Guzmán et al., 2011) by diminishing the need for fallow and importing nutrients from distant territories, instead of transferring them from woodland and pastureland. Additionally, the new industrial inputs reduced the labour needed to manage the agroecosystem. However, the beginning of the industrialized management was combined with some traditional features that proved useful for the sustainability of the agroecosystem. External inputs were complemented with the recirculation of nutrients through biomass reuse. The dependence on non-renewable resources that the introduction of modern technologies implied could probably be environmentally bearable as long as these industrial inputs were used at a small scale, but it introduces a new tension between the sustainability at the local and global scales: a metabolic rift (Bellamy, 1999).

6. *Conclusions*

Sustainable management of agroecosystems has been a hard task throughout history. The aboveground and belowground analysis presented in this chapter reveals that the challenges faced and the solutions adopted to keep farm systems sustainable over time depended on multiple dimensions, and have been affected by different ecological, technological and socioeconomic factors. However, sustainability is not a fixed condition, but a dynamic process. In this sense, the results of our historical analysis reflect that a more productive agroecosystem does not mean a more sustainable one. The main reason for that is having given up the sustenance effort devoted to reproduce the living funds of the agroecosystem through local renewable biomass flows by keeping a multi-purpose and integrated management adapted to the site-specific ecological and socioeconomic conditions. When the availability of cheaper external inputs of industrial origin, coming directly or indirectly from non-renewable fossil fuels, made that effort no longer necessary, its manifold agroecological virtues came also to an end. Sustainable management of agroecosystems needs to deal with different tensions and balances, and our case study reflects the strain over the renewability of resources and between different scales of analysis: crop system, agroecosystem and global levels. In order to deal with these tensions and multiple balances of the art of farming (Netting, 1993; Van der Ploeg, 2013), the study of traditional integrated management practices can offer useful insights for better prospects of sustainability.

Chapter 4: Searching on the Art of Farming: Socio-ecological analysis of a traditional Mediterranean silvoarable crop system (Les Oluges, Catalonia, c.1860)[12]

Abstract

The expansion of the Green Revolution throughout the second half of the 20th century led to a great homogenization of cropland under monoculture crop systems which are linked to some of the ecological and social problems of modern agriculture. The potential of polycultures for the implementation of more sustainable agricultural systems is highlighted by agroecological approaches, and traditional farming practices can be a great source of knowledge on this respect. This chapter focuses on the study of the traditional intercropping system present in Les Oluges until the mid-20th century. It analyses the advantages that this crop system could entail from a socioeconomic and agroecological perspective. The results obtained point out to the complexity of traditional farm management that required to satisfy multiple aims and opens the way for more research needed to understand and recover the knowledge embedded in traditional Mediterranean polyculture systems.

1. *Introduction*

The spread of the Green Revolution from the mid-20th century caused a major change in agricultural landscapes and farming practices. Mediterranean agricultural landscapes were traditionally diverse and heterogeneous, integrating different land uses in agroecosystems and sometimes mixing different crops within the same plot. However, agricultural modernization transformed most of this polyculture landscapes into homogeneous land covers of single crop systems. The aim of this new model of agriculture was to increase cropland productivity in order to meet the demands of an expanding global population and the upscaling of the dietary ladder towards higher meat and dairy intake unhealthy for the people and the ecosystems (Soto et al., 2016; Tilman

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[12] This chapter was elaborated during my stay at the Università degli Studi di Scienze Gastronomiche di Pollenzo (UNISG), under the supervision of professor Paola Migliorini. I carried out the analysis, considering the possible measures that could be employed, and wrote this chapter. Paola Migliorini, provided her advice in order to improve the clearness of the results presentation. Additionally she, together with Enric Tello and José Ramón Olarieta, helped me discussing the results.

& Clark, 2014). The use of improved seeds and synthetic fertilizers raised productivity of cultivated soils, and motor-machinery reduced the need of agricultural labour. Additionally, pesticides were widely used to protect harvests from pests. The Green Revolution succeeded in the achievement of higher agricultural outputs, but incurring in significant ecological and social costs (Evenson & Gollin, 2003). Monocultures and improved seeds, selected for their high yields, lack the defensive mechanisms of locally adapted traditional seeds and mixed crops, being more prone to pest attacks (Conway, 2005; Yapa, 1993). The continued cultivation of soil with the same crop depletes soil fertility. Furthermore, the specialization of agricultural systems reduces biodiversity, weakening the capacity of agroecosystems to provide ecological services. All this increases the need of external inputs for the industrialized management of agriculture (Altieri & Rosset, 1996; Conway & Pretty, 2009; Tilman, Cassman, Matson, Naylor, & Stephen Polasky, 2002). Additionally, mechanization reduces the need of labour in farmland, and the diminishing prices of agricultural products because of the higher supply, together with the increasing dependence on increasingly costly industrial inputs, leads in many cases to precarious subsistence for farmers and the depopulation and abandonment of rural areas (Conway & Barbier, 1990; Pretty, 2005) .

Facing these problems, agroecology proposes that the study of traditional farm systems, based on an integrated management of multiple land uses and multiple cropping systems, can provide a basis for developing more sustainable and fair agricultural systems (Altieri & Koohafkan, 2017; Gliessman, 1985; Pretty & Bharucha, 2018; Schutter & Vanloqueren, 2011). This chapter analyses the traditional polycultures present in Les Oluges, an agroecosystem from the inner part of Catalonia. In order to understand the advantages of polyculture the analysis is carried out from a double perspective. On the one hand, the biophysical analysis is grounded on an agroecological point of view, taking into consideration the productivity, resilience and sustainability of crop systems. On the other hand, the socioeconomic approach is based on a Chayanovian point of view of the peasant economy considering that the productive decisions of traditional farmers were not based solely on the maximization of output or income, but involved more complex arrangements that led to optimize site-specific balances pondering the consumption needs and the labour capacities, as well as the irreplaceability of resources (Chayanov, 1966; Van der Ploeg, 2013).

There is a growing interest in the study and implementation of more diverse crop systems in order to reduce the environmental costs of modern industrialized monocultures. New researches have expanded the terminology used, and there are various terms we can use for defining the crop systems in our case study. The broadest concepts are polyculture (Agnoletti & Emanueli, 2016) or multiple cropping system (Stephen R Gliessman, 1985), which refer to the cultivation of two or more crops in the same piece of land, either simultaneously or consecutively. The concept of intercropping (Vandermeer, 1989) is used for those polycultures that combine different crops in the same field and at the same time. Additionally, agroforestry (Nerlich, Graeff-Hönninger, & Claupein, 2013), alley cropping (Grebner, Bettinger, & Siry, 2013) and silvoarable systems (Eichhorn et al., 2006; Rigueiro-Rodríguez et al., 2009), refer to those intercropping systems that combine woody perennial crops with agricultural annual crops and/or livestock breeding. Given that the polycultures of Les Oluges, which combined cereals, vines and olives, fall under any of these definitions, all these terms will be used throughout this work.

2. *Historical overview of the agroecosystem of Les Oluges*

2.1. Biophysical and socioeconomic context

Our case study is located in the Segarra County (Lleida province), in the inner part of Catalonia. The climate of this area is Dry Mediterranean Continental, with low average annual rainfall (less than 500 mm), a period of water stress that runs from April to October (Ramon Garrabou et al., 1999), cold and foggy winters, hot and dry summers, and frequent adverse climate events that jeopardize harvests. Thus, traditional agricultural practices in Les Oluges needed to be adapted to low cropland productivity and high climate variability and risk.

The historical changes of the structure and functioning of Les Oluges agroecosystem have been explained in previous works (Díez et al., 2018; Díez, Olarieta & Tello, forthcoming) with more detail, but it is important to highlight here some of the relevant features for our current analysis. Historically, agriculture in Les Oluges has been mainly dedicated to grow cereals, but other Mediterranean crops were also present, such as vines, olives and almonds. Traditional agricultural management was able to cope with the ecological constraints by adopting an integrated use of local resources, which combined the use of livestock, woodland and cropland for sustaining the productive capacity of the agroecosystem. In the second half of the 19th century, an intensive use of woodland made up for the low cropland productivity. Woodland was a source of animal feed, fertilization resources, and surface for cropland expansion (Díez et al., 2018). Additionally, the composition of livestock used as draft force was also adapted to the limited feed resources, with donkeys being the most abundant draft animals. With a relatively high population density (42 inhabitants/km^2, well above the average in the Lleida province and quite optimal for viticulture (Badia-Miró & Tello, 2014)) and under favourable market conditions, vine cultivation expanded in Les Oluges in this period, extending the polyculture crop system in which vines and cereals were grown in association.

In the 20th century, after the *phylloxera* plague destroyed most of the vines in Les Oluges, the silvoarable system did not disappear. The turn-of-the-century agricultural crisis spurred a process of depopulation that continued throughout the whole century. However, by the 1950s and 60s the agroecosystem started to adopt some of the technologies of the Green Revolution. Higher cropland productivity was achieved with the use of new seeds and the introduction of mineral fertilizers and tractors, but the traditional agroforestry system was maintained. The number of hectares grown under multiple cropping was similar to that of 1860, but in this period, the intercropping system was diversified introducing a greater presence of olives and almonds in the crop associations. However, by the end of the century, the full mechanization and industrialization of the agroecosystem erased the polyculture landscape with the spread of grain monocultures.

2.2.The relevance of the alley cropping system in Les Oluges

The relevance of polyculture systems in traditional agroecosystems and for the sustainability and resilience of farming practices is widely acknowledged in agroecology and landscape ecology (Altieri & Rosset, 1996; Biasi, Brunori, Ferrara, & Salvati, 2017; Gliessman, 1985; Moreno et al., 2018; Wezel et al., 2014). Furthermore, our previous analysis revealed that the silvoarable cropping system was a key element for the functioning of the Les Oluges agroecosystem. In the mid-19th century, with a relatively high rural population density and low cropland productivity, it was a way to make a more intensive use of cropland taking advantage of the market conditions without overlooking subsistence needs. However, in the mid-20th century, with half the previous population, the introduction of the first industrial inputs and much higher cropland productivity, the conservation of the alley cropping system could probably respond to other aims. The maintenance of the traditional intercropping system introduced a greater diversity of crops, and was an important feature that allowed increase the agroecosystem energy efficiency and sustainability in socioeconomic and agroecological terms.

The lack of local specific data for the mid-20th century does not allow to analyse in sufficient depth the silvoarable system in that period. Thus, the analysis will focus on the associated crops that were present in 1860, understanding that, with due caution, some of the results could be extrapolated to the crop systems of the following century up to the 1970s or 1980s.

Moreover, the possibility of extending the results obtained to different temporal and geographical contexts is important because the presence of this intercropping system was not restricted to Les Oluges. The Mediterranean polyculture was widely spread throughout South Europe (Agnoletti, 2013; Agnoletti & Emanueli, 2016; Colomba, 2017), and there are records showing that the association of vines (and olives and other Mediterranean woody crops) with cereals (and other annual crops) was quite ubiquitous in Catalonia and all over Spain (Elías Pastor, 2016; Junta Consultiva Agronómica, 1889). Unfortunately, further from some short mentions that assert its existence, it has not been possible to find sufficient data to compare its productivity or obtain explanations about the rationality behind the adoption and long maintenance of this crop system. This research is an attempt to explore this issue.

3. *Sources and methodology*

The basic source used for this investigation is the *Cartilla evaluatoria* of Les Oluges for 1883, a local agricultural survey made for tax purposes. This historical source provides the accounts of the produce and costs associated to different crops systems of Les Oluges. Since this document was elaborated for calculating taxes, it does not reflect the actual productivity and costs of each year and piece of land, but an agreed estimation of the mean produce and requirements that should be close to reality in order to avoid tax fraud or social unrest. The information from the *Cartilla evaluatoria* was combined with the distribution of land uses registered in the *Amillaramiento* of Les Oluges for 1860, and with the cattle census of 1865. The *Cartilla evaluatoria* provides data for a greater variety of crop systems than the ones that were actually registered in the *Amillaramiento* of 1860. Even though some changes in the land uses can be expected from 1860 to 1883, this analysis will focus on the most abundant crop systems included in the land use register, providing the results for the minor crop systems in the Annex.

The methodology used compares the polycultures and monocultures from various points of view: productivity, labour requirements, energy efficiency, and soil nutrient cycling and balances. Thus, traditional theoretical perspectives on agricultural systems are combined with more recently developed perspectives of agroecology and social metabolism approaches. The aim is to assess the possible advantages and disadvantages of the poly-cultural and mono-cultural crop systems taking into consideration the multiple dimensions that may affect the decision-making process of traditional farmers. The indicators have been estimated considering the best possible management of one hectare of each crop system, given the characteristics of the agroecosystem and the agricultural practices of Les Oluges in the second half of the 19th century. Cereals are considered to be left fallow every other year, either in monoculture and in polyculture. Additionally, according to the prevalence of donkeys in the composition of livestock, the annual feed needed to sustain one donkey has been taken as the measure to assess the capacity of each crop system to maintain the draft force needed for its cultivation and transport. Finally, even though the use of *formiguers*[13] was only recorded in the *Cartilla evaluatoria* in vegetable gardens and cereal monocultures, the use of *formiguers* has been considered in all the crop systems that include vines in order to optimize the possible uses of the resources provided by each crop system, given that the use of vine pruning for this fertilization technique was widespread in the traditional agricultural practices in Catalonia (Galán, 2017; Olarieta et al., 2011).

4. *The agroecosystem of Les Oluges and its silvoarable system in 1860*

The distribution of farmland in Les Oluges in 1860 (Table 13) was shared quite evenly between cropland and woodland (47% and 44% of total farmland respectively). In cropland, the predominant crop systems were cereal monoculture and especially the agroforestry system that combined cereals and vines (36% and 61% of the cultivated area respectively). It is worth noting that vines were only cultivated in intercropping systems, either with cereals or with cereals and olive trees, and there was no vineyard monocrop. Additionally, the distribution of crop systems in the different land qualities followed a significant pattern. These land qualities did not indicate only the physical conditions of soils, but make reference also to the suitability of the different plots for different crops and their distribution. This is clearly seen in the distribution of cereals in monocultures

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[13] This was a traditional fertilization and soil conditioner technique that consisted on building piles of wood, covering them with soil and burning them for burying the charcoal and some ashes in the cropland afterwards (Olarieta et al., 2011).

and polycultures. Wheat was cultivated in the land of first quality, barley in the land of second quality, and rye in third quality land.

Table 13. Land uses in Les Oluges the second half of the 19th century. Source: Our own, from the sources detailed in the text.

Land uses (ha)	Land qualities			Total Hectares
	1	2	3	
Vegetable gardens	3.03	1.25	0.00	4.28
Cereals	47.29	114.02	160.20	321.52
Olive trees	0.00	0.00	0.18	0.18
Cereals and olive trees	0.65	7.84	13.62	22.12
Cereals and vines	27.42	156.96	355.87	540.25
Cereals, vines and olive trees	0.00	0.00	0.15	0.15
Woodland	16.42	128.16	686.27	830.84
Pastureland				155.80
Total	94.81	408.24	1216.28	1875.13

The most abundant land uses correspond to soils of second and third quality, either for monocultures and polycultures, with the exception of vegetable gardens. Indeed, 40% of cropland was cereals (rye) and vines of third quality.

Additionally, Table 14 shows that the distribution of crop systems was quite similar among landowners. Total farmland included cropland, woodland and pastureland.

Table 14. Distribution of the main crop systems in Les Oluges by land ownership size. Source: Our own, from the sources detailed in the text.

Quintile	Total farmland (ha)	Mean (ha)	Cropland (% of farmland)	Cereals & vines polycultures (% of cropland)	Cereal monocultures (% of cropland)
1	55.66 - 13.88	23.62	54%	53%	43%
2	11.99 - 3.99	6.97	62%	67%	28%
3	3.99 - 2.18	2.96	74%	76%	21%
4	2.11 - 1.05	1.6	68%	76%	22%
5	1.02 – 0.00	0.56	88%	66%	27%

Those with larger farmland properties, tended to have a greater proportion of woodland and pastures and a larger share of cereal monocultures in their property, which reflects also their tendency to grab best quality lands. Medium and small landowners had 66-76%

of their cropland cultivated with cereals and vines polyculture, and only 21-28% of their cropland was for grain monoculture. The differences on the distribution of crop systems among small and large landowners were not that large, indicating that the choice between cereal monoculture or the intercropping system was not related to the abundance of soil resources of the farming unit only, but the quality of the soils predominant in Les Oluges was also determinant. Given the scarcity of soils of good quality for growing cereals alone, most of the landowners dedicated an important share of their cropland to the cultivation of a polyculture of vines and cereals. Furthermore, the *Cartilla evaluatoria* indicates that in the context of cropland expansion, deforested soils were mainly cultivated with the silvoarable system of vines and cereals.

5. Results

5.1. Land Equivalent Ratio (LER)

The main measure for the comparative analysis of the intercrop and monoculture systems is the Land Equivalent Ratio (LER), which compares the relative land requirements of the intercrop and the monocultures, giving a measure of how much land would be needed to obtain the same produce in monocultures as in the alley cropping system (Vandermeer, 1989). The LER is the sum of the relative yields. When it is higher than 1, the polyculture is more efficient, or has advantage over the monoculture. As detailed in the Annex, the LER has been calculated considering the energy content of the main produce and the by-products of each crop.

Table 15. Land Equivalent Ratio (LER) of the polyculture crop systems registered in the local agricultural survey of Les Oluges (1883). Source: Our own, from the sources detailed in the text.

Crop systems	**LER**		
	1Q	2Q	3Q
Vines & olive trees	1.05	1.07	0.98
Cereals & vines	0.97	1.00	0.97
Cereals & olive trees	1.02	1.00	0.90
Cereals, vines & olive trees	1.08	1.07	1.09

The LER obtained for the different polyculture systems of Les Oluges (Table 15) are all close to 1, indicating a similar productivity of the crops both in the monocultures and polycultures. Thus, it cannot be concluded that the alley cropping systems were more energy efficient than the monoculture, at least according the results obtained with the relatively low accuracy of our sources. These results are conditioned by the fact that the *Cartilla evaluatoria* of Les Oluges established generally the same productivity of crops in monocultures and polycultures. This could seem suspicious, but the sources found for other villages nearby which allow comparing only cereals in monoculture and polyculture offer similar or even higher productivities for cereals in polyculture with vines than in monoculture. Thus, despite needing to be cautious with these results, it is possible to affirm the lack of disadvantage for the mixed crop systems. Efficiency was similar for monocultures and polycultures, with no clear advantage for any of these crop systems in terms of land productivity in energy terms. These results are similar to those obtained by Trenbath (1974) on a comparison of 572 multiple crop systems, with most of them obtaining a LER close to 1.

Interestingly, those polycultures that would have a larger advantage over monocrops were not present in the agroecosystem studied (such as the mix of vines and olives), or were present in very small share of cropland (such as the silvoarable system including cereals, vines and olives). The fact that those crop mixtures that include olive trees tended to have higher LER values is mainly related to their by-products with a high energy content (green shoots used for animal feeding, firewood obtained from pruning, and pomace and olive bones obtained after pressing the olives; see Infante-Amate & González de Molina, 2013).

Additionally, given that the cultivation of vines was mostly for commercial purposes and that the LER results are close to 1, an approximation to the Income Equivalent Ratio can be calculated, in order to assess the possibility of an economic advantage of the intercrop of vines and cereals. Following Vandermeer (1989), in this case the comparison is made taking into account only the most valuable of the monocultures, which was vineyard. Comparing the net incomes in money terms of the intercropping of vines and cereals, and vines as single crop, the results obtained were 0.85, 0.89 and 1.00 for first, second and third qualities respectively. There are two ways of reading these results. Considering the economic returns, alley cropping was not advantageous in economic terms except for third quality soils in which there was neither advantage nor disadvantage. However, taking into consideration the tax purpose of the historical sources, alley cropping of vines with cereals can also be considered advantageous viewing the results in terms of a lower taxation compared to the monoculture of vines.

5.2. Labour requirements and seasonality

A measure similar to the LER was estimated for analysing the labour requirements of the polycultures and assess if they were advantageous in labour terms. The Relative Total Labour Costs compares the labour needed for each crop system, either in days per hectare or in monetary terms (pesetas/ha). In this case, a value below one would indicate a lower labour cost and an advantage either in time or money terms of the polyculture over the monoculture.

Table 16. Relative Total Labour Cost of the crop systems of Les Oluges in days and monetary terms. Source: Our own, from the sources detailed in the text.

Crop systems	**Relative Total Labour Cost**					
	Days			**Pesetas**		
	1Q	2Q	3Q	1Q	2Q	3Q
Vines & olive trees	1.07	1.03	0.95	1.01	0.98	0.84
Cereals & vines	1.10	1.05	1.00	1.07	1.02	0.91
Cereals & olive trees	1.30	1.23	0.96	0.97	0.95	0.77
Cereals, vines & olive t.	1.30	1.31	1.37	0.99	1.00	0.97

The results obtained (Table 16) in days of work measured in time are not favourable for polycultures. The values of the Relative Total Labour Cost in days/ha show values higher or close to one, revealing that the monoculture would require a lower labour investment, and would therefore be more advantageous in work terms—as expected, given that growing cereals were also less labour intensive than growing vines (Badia-Miró & Tello, 2014). However, the same calculation made in monetary terms reveals an opposite result, with most of the figures being close or lower than one, what would indicate an advantage of the polyculture over monoculture regarding the costs of labour. These results indicate that despite requiring more days of work, the labour invested in polycultures was less expensive. Two elements explain these labour savings in monetary terms: the reduced need for ploughing, and the higher share of female work in the intercropping system.

Ploughing was the most expensive task since it required a pair of powerful draft animals and a man. It had a cost of 10 pesetas/day including the cost of hiring the animals and a man. On the contrary, female labour (hired for those tasks considered less intense) was the cheapest, costing 1 peseta/day (half of the man’s wage). Table 17 shows the relative needs of ploughing and female work in each crop system. The reduced need for ploughing in the silvoarable systems is explained by the smaller area that was ploughed. Considering that the management of cereals included fallow every other year, one hectare of grain monoculture can be considered half sown, half fallow each year. The ploughing of that half hectare of fallow surface required between 1.75 and 3 days, with more days worked in the soils of best quality. In one hectare of vines and olives, either as single or mixed crop, the number of days required for ploughing the space between the lines of the woody crops was higher, between 3.5 and 6 days. However, in one hectare of the silvoarable systems that combined cereals and woody crops, the area occupied by the rows of vines has to be discounted as it was only dug by hand. Therefore, half of the spaces between the woody crops would be sown, and only the other half of these spaces (those left for fallow) needed to be ploughed. Ploughing work was therefore reduced to between 1.75 and 1 days.

Regarding female work, each crop had at least one task traditionally done by women. According to the *Cartilla evaluatoria*, days of women work were more abundant in the monocultures of vines and olives, where female work was used for harvesting, requiring between 2 and 12 days of work per hectare in vineyard and between 14 and 33 days of female work in olive groves. In cereals, women worked between 1 and 3 days per hectare weeding the cropland.

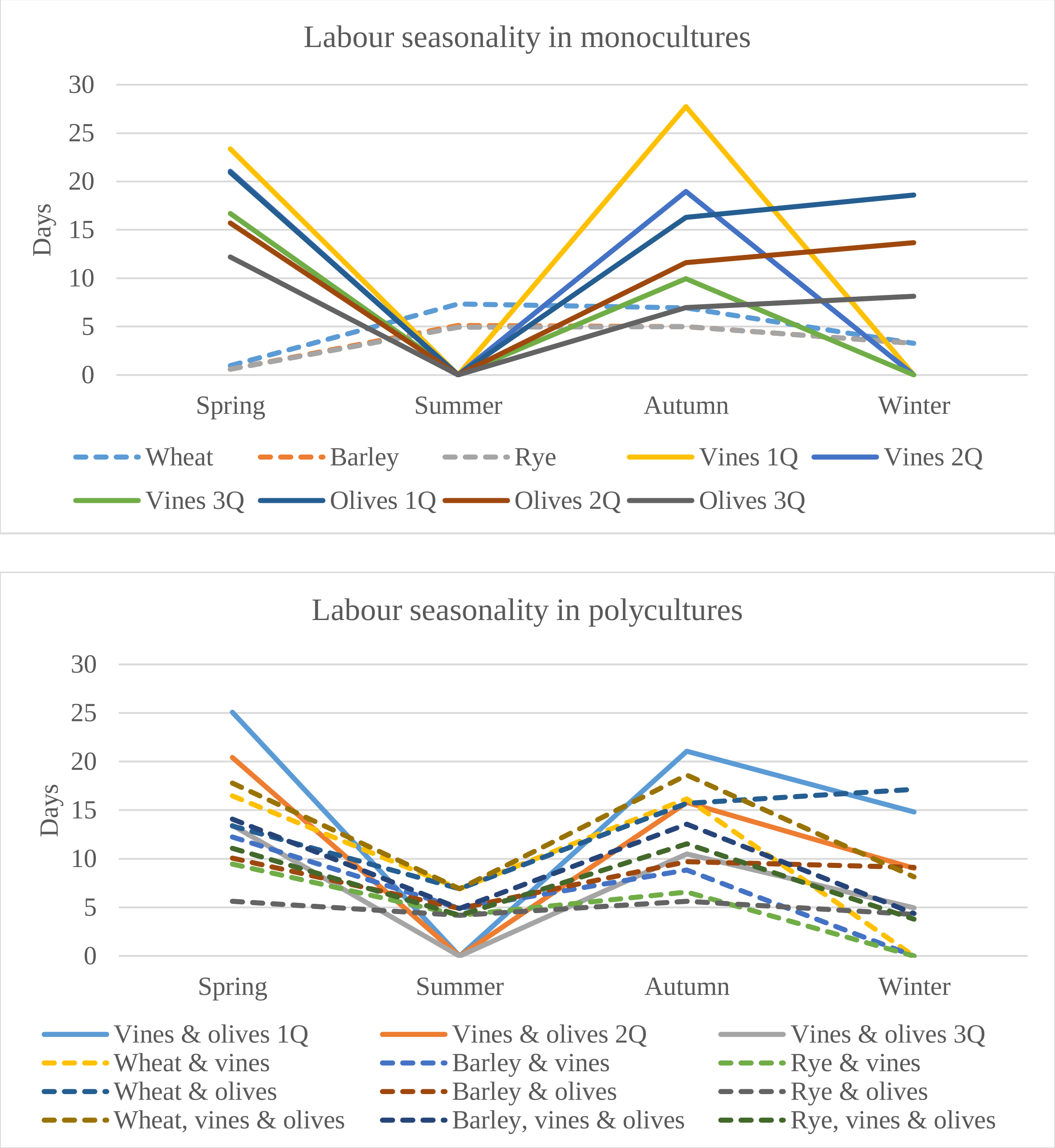
Table 17. Share of ploughing and female days of work over the total working days for the crop systems of Les Oluges. Source: Our own, from the sources detailed in the text.

Crop systems	**Days of ploughing (% of total working days)**			**Days of female work (% of total working days)**		
	1Q	**2Q**	**3Q**	**1Q**	**2Q**	**3Q**
Cereals	37%	31%	31%	12%	6%	6%
Vines	40%	42%	49%	23%	17%	9%
Olive trees	46%	45%	51%	58%	57%	51%
Vines & olive trees	39%	39%	42%	46%	41%	40%
Cereals & vines	20%	23%	22%	29%	21%	17%
Cereals & olive trees	17%	21%	25%	53%	47%	37%
Cereals, vines & olive t.	17%	18%	18%	40%	34%	36%

Another useful approach to the labour requirements of monocultures and polycultures in Les Oluges is the analysis of their distribution throughout the year, i.e. the evenness or unevenness of labour seasonality.

Figure 12 shows the distribution of days of work needed per hectare of each crop system throughout the year. Woody crops had a greater seasonality, with minimum work requirements in summer, at the same moment when the demand of work in cereal monocultures peaks.

Figure 12. Days of work by season required on each crop system in Les Oluges (1Q: first quality soil; 2Q: second quality soil; 3Q: third quality soil). Source: Our own, from the sources detailed in the text.



The distribution of working days in monocultures is reflected and nuanced in polycultures. The seasonality of agroforestry system that combined vines and olives was similar to the monocultures of these crops. However, seasonality was reduced in the silvoarable crop systems that include cereals with woody crops.

5.3. Energy analysis and nutrient balances.

Two important criteria for analysing the efficiency and sustainability of agroecosystems from a biophysical point of view is the study of the energy and nutrient balances. A scheme of the main flows of energy and nutrients of each crop system has been estimated according to the traditional agricultural practices used in Les Oluges. In pursuit of clarity of the analysis, the focus here will be on the most widespread crop system: the intercropping of vines and cereals. However, the results for all the crop systems is provided in the Annex[14], together with a description of the main flows of energy and the basic assumptions made for building the energy profiles and nutrient balances.

Figure 13 shows the diagram of the main energy flows in cereal monoculture (Figure 13a), vine monoculture (Figure 13b) and the silvoarable system that combined vines and cereals (Figure 13c). Only cereal monoculture and the intercropping of vines and cereals were actually present in Les Oluges in the second half of the 19th century, but vineyard monoculture is included for allowing the comparison of the polyculture with the corresponding monocultures.

The graphic representation of the energy flows shows the complexity of the energy functioning of each crop system through the connections with other fund elements of the agroecosystem. Cereal monocultures were the most culturally valued and favoured crop system when the best land was allocated, given their key relevance for subsistence. They were usually placed in the best pieces of dry land, and even though it was strictly needed to leave the land fallow every other year, this was the only crop system that received fertilization from manure if there was availability of this scarce resource. Furthermore, wood from other land uses, such as woodland and scrubland, was needed to build *formiguers* in cereal monoculture. In vineyards, the fertilization resources came from this same crop system, as vine pruning was used for building *formiguers* or as fresh buried biomass, a common practice in other parts of Catalonia at that time (Tello et al., 2012).

Figure 13. Scheme of the flows of energy of some of the crop systems in Les Oluges. 13a) Cereals monoculture, 13b) Vineyard monoculture (1Q: first quality soil; 2Q: second quality soil; 3Q: third quality soil) , 13c) Cereals and vines intercropping (W&V: intercropping of wheat and vines in first quality soil; B&V: intercropping of barley and vines in second quality soil; R&V:

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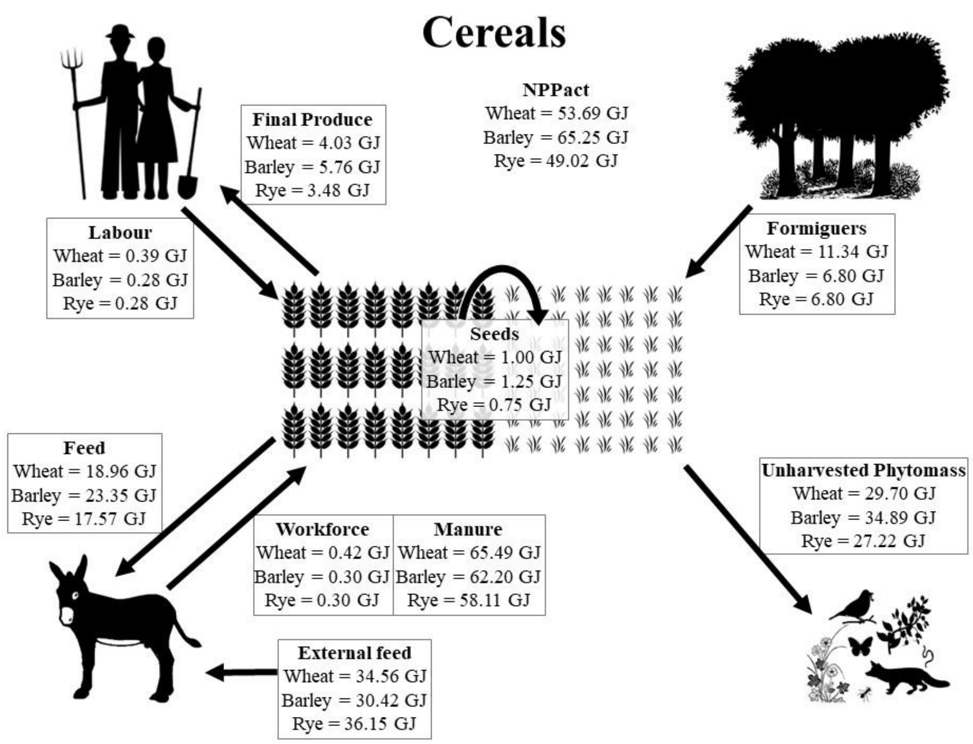
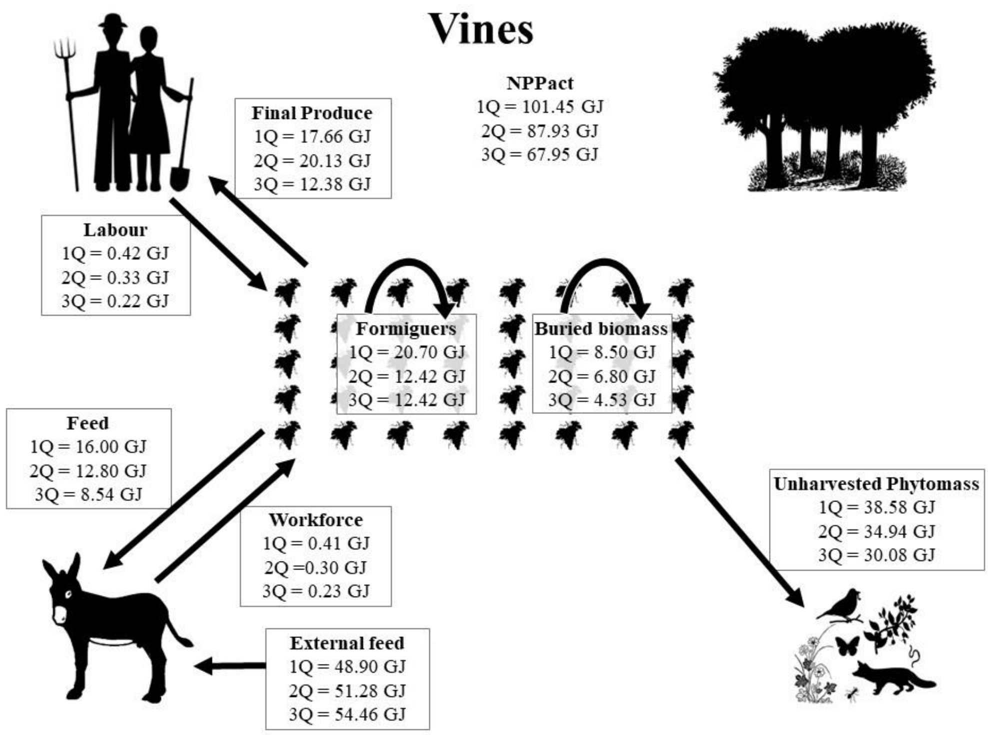
[14] Management of woody crops was comparable. The results for the crop systems that include olive trees are similar to those of the vineyard with the singularity that olive crop systems received no reinvestment of biomass for fertilization.

intercropping of rye and vines in third quality soil). Source: Our own, from the sources detailed in the text.

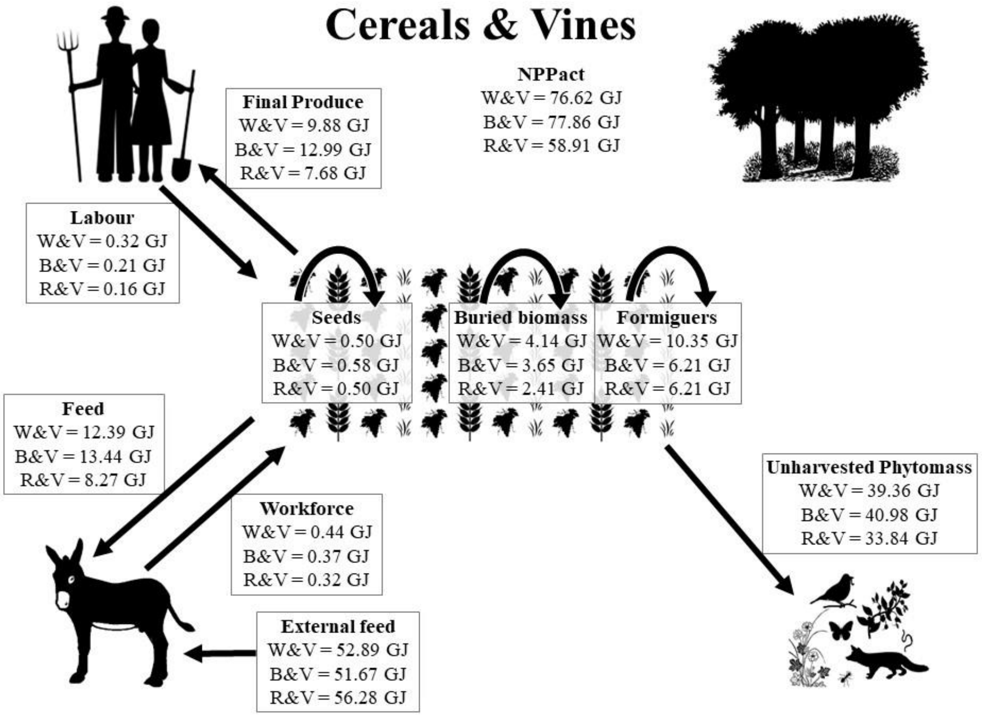
13a)



13b)



13c)



The management of the silvoarable system that mixed vines and cereals was similar to the management of vines in monoculture. The fertilizing resources were reuses of the by-products, and no manure was applied on the cereals grown between the vines.

The distribution of the energy flows that make up the NPP_{act} of each crop system (Table 18) shows that the greatest part of the energy produced remained as Unharvested Phytomass in all the cases. However, the part that was appropriated and managed by humans was distributed quite different in each crop system. Cereal monocultures provided the greatest share of energy for animal feed, while the share of energy for human use was rather low. Additionally, cereal monocultures were mainly fertilized through external biomass inputs, thus only seeds were recycled in cropland. Vines monoculture and the silvoarable system had a more even distribution of the NPP harvested. Looking at the NPP distribution, the intercropping system could have advantage over the monoculture of cereals regarding the Final Produce, while also being more advantageous than vine monoculture regarding animal feed.

Table 18. Distribution of the NPP_{act} according to the energy flows of each crop system. Source: Our own, from the sources detailed in the text.

Crop systems		**NPP_{act} distribution**			
		Unharvested Phytomass	**Final Produce**	**Animal feed**	**Recycling (seeds and fertilization)**
Wheat		55%	8%	35%	2%
Barley		53%	9%	36%	2%
Rye		56%	7%	36%	2%
Vines	1Q	38%	17%	16%	29%
	2Q	40%	23%	15%	22%
	3Q	44%	18%	13%	25%
Wheat & vines		51%	13%	16%	20%
Barley & vines		53%	17%	17%	13%
Rye & vines		57%	13%	14%	15%

Additionally, the nutrient balances of these crop systems (Table 19) reflect their different managements. Cereal monocultures were the only crop system with positive nutrient balances, thanks mainly to the great effort put in the replenishment of soil fertility through the use of manure. Without manure fertilization, vine monoculture and the silvoarable system did not recover the nutrients extracted, but the lower extraction of nutrients in the silvoarable system allowed to obtain smaller deficits, maintaining the productive capacity of soil under the intercropping system for a longer time.

Table 19. Nutrient balances (kg/ha) of the main macronutrients (Nitrogen (N), Phosphorus (P), and Potassium (K)) for cereals monoculture, vineyard monoculture (1Q: first quality soil; 2Q: second quality soil; 3Q: third quality soil) and the silvoarable system of cereals and vines W&V: intercropping of wheat and vines in first quality soil; B&V: intercropping of barley and vines in second quality soil; R&V: intercropping of rye and vines in third quality soil). Source: Our own, from the sources detailed in the text.

Nutrient balances		N/ha	P/ha	K/ha
Cereals	Wheat (W)	2.61	2.88	13.56
	Barley (B)	1.72	2.25	8.41
	Rye (R)	4.26	1.83	11.55
Vines (V)	1Q	-34.12	-2.95	-17.01
	2Q	-25.76	-2.59	-14.75
	3Q	-17.52	-1.53	-9.54
Cereals & vines	W&V	-18.45	-2.11	-9.96
	B&V	-16.03	-2.18	-11.18
	R&V	-10.12	-1.68	-6.43

According to the energy analysis, each of the crop systems had some advantage. Vineyard was the crop system that provided most energy available for human use (FP), even though this is in part an effect of the high energy content of the woody by-products used as fuel or fertilizer. Cereal monoculture provided the greatest animal feed, with one hectare affording up to 40-50% of the annual needs of a donkey, while one hectare of vines monoculture and the intercropping of vines and cereals, respectively, only allowed to meet 20% and 15% of the donkey annual needs at most. Finally, the silvoarable system had the lowest labour requirement in energy terms (considering not only the amount of days of work but also its intensity –or 'drudgery' (Chayanov, 1966), with more demanding tasks consuming more energy per unit of time—, and a labour productivity measured in energy terms higher than the one of cereal monocultures and similar to that of vine monocultures (the ratio of GJ obtained as Final Produce divided by those invested as labour in cereal monocultures was between 10-21 GJ, while being 42-61 GJ in vines monoculture and 38-62 GJ in the intercropping system).

The energy efficiency of these crop systems can also be analysed using some of the EROIs (Energy Return On Investment ratios) that have been employed in the study of traditional and modern agroecosystems in previous works (Guzmán et al., 2018; Guzmán & González de Molina, 2015; Tello et al., 2016; 2015). The Final Energy Return On Investment (FEROI) indicates the energy efficiency of the crop system for the provisioning of human needs, dividing the Final Produce by the total energy invested or Total Inputs Consumed (TIC) as Biomass Reused and External biomass Inputs. The

Biodiversity Return measures the efficiency of the agroecosystem for sustaining associated biodiversity and is estimated dividing the total energy content of the phytomass produced through the photosynthesis (NPP_{act}), by the Unharvested Phytomass, i.e. the above and belowground biomass that has not been directly managed by humans and remains available to potentially sustain associated biodiversity (which can provide important ecosystem services). Finally, the NPPEROI provides a measure of the total energy efficiency of the agroecosystem in terms of photosynthetic biomass produced.

Table 20 shows that the monoculture of vines has the highest energy efficiency for all the EROIs considered, while the monoculture of cereals has, by far, the lowest energy efficiency. These differences reflect the different management practices of each crop system. Cereal monocultures were the crop system that received a higher energy investment, especially through manure, in order to sustain soil fertility. Thus, its lower energy efficiency indicates the great effort put in the sustenance of the productive capacity of cereal monocultures. Additionally, the fact that the EROIs of the silvoarable system were closer to those of the monoculture of vines indicates the similarities in the management of these two crop systems.

Table 20. Main agroecological EROIs (Energy Return On Investment ratios) for some of the cropping system in Les Oluges (1Q: first quality soil; 2Q: second quality soil; 3Q: third quality soil). Source: Our own, from the sources detailed in the text.

EROIs	**FEROI**[a]			**BIODIVERSITY**[b]			**NPP_{act}EROI**[c]		
	1Q	**2Q**	**3Q**	**1Q**	**2Q**	**3Q**	**1Q**	**2Q**	**3Q**
Wheat	0.05			0.28			0.50		
Barley		0.08			0.33			0.62	
Rye			0.05			0.29			0.53
Vines	0.39	0.62	0.48	0.46	0.52	0.54	1.20	1.29	1.22
Cereals & vines	0.36	0.54	0.44	0.59	0.63	0.66	1.14	1.20	1.15

[a] Final EROI = Final Produce / Total Inputs Consumed

[b] Biodiversity Return = Unharvested Phytomass / (Total Inputs Consumed + Unharvested Phytomass)

[c] NPP_{act} EROI = NPP_{act} / (Total Inputs Consumed + Unharvested Phytomass)

The Biodiversity Return shows that the silvoarable system, besides including higher crop diversity, had also a greater capacity to sustain associated biodiversity, which can be related to the provision of ecological services such as pest control.

6. *Discussion*

The results obtained allow us to examine the possible rationality behind the implementation, expansion and maintenance of the silvoarable system in Les Oluges. Multiple cropping systems have advantages and disadvantages (Gliessman, 1985). However, the widespread use through time and space of intercropping systems in Les Oluges and in the Mediterranean landscapes, points to greater advantages than disadvantages, at least until the spread of motor mechanization in the second half of the 20th century. Thus, this discussion will focus on the analysis of the advantages of the polyculture. These advantages can be divided in two main types: those referred to the agronomic-biological dimensions, and those referred to the socio-economic aspects.

6.1. Agroecological interactions

The results of the LER suggest that there was a weak competition between the crops used in the polycultures in Les Oluges. This is not an unusual result (Trenbath, 1974; Vandermeer, 1989) as the productivity of polycultures is usually similar or above that of the corresponding monocultures. As Vandermeer (1989) mentions, the fact that the LER shows an advantage (or in our case a lack of disadvantage) of the intercrop over its monocultural components "may not require any special explanatory mechanism, any more than the coexistence of two species requires any further explanation other than they do not affect one another strongly enough to cause extinction. Yet, in the sense that they are grown in the same field but do not compete intensively, the lack of competition may require some sort of explanation" (pp. 32-33). There is limited availability of scientific records that analyse the agronomic interactions in the intercropping of vines and cereals outside the use of the latter as cover crops in vineyards. However, some possibilities can be mentioned.

One of the mechanisms affecting the reduced competition between cereals and vines is niche differentiation (Tilman, Reich, et al., 2001; Tilman, Wedin, & Knops, 1996; Vandermeer, 1989). Niche differentiation means that the existence of different cycles of water and nutrient absorption of each crop avoids intense competition for water and nutrients. On the one hand, the highest demand for nutrients by cereals occurs between tillering and stem elongation (from autumn until spring; see García-Serrano Jiménez et al., 2009), when the vine is in a dormancy period and using resources already accumulated; on the other hand, the highest demand of vines takes place during flowering and veraison (in summer; see Ripoche, Metay, Celette, & Gary, 2011), when the cereal has been harvested. Furthermore, grapevines could adapt their rooting and water and nutrient uptake when intercropped, which could be a mechanism of productive competition (Cardinael et al., 2015; Celette, Findeling, & Gary, 2009; Celette, Gaudin, & Gary, 2008).

In addition, several studies propose that agroforestry systems in general, and those that include vine cultivation in particular, help increase insect biodiversity, providing protection against pests among other ecological services (Altieri & Nicholls, 2002, 2004; Diane, Francis, Nicholls, & Altieri, 2004; Moreno et al., 2018; Nerlich, Graeff-Hönninger, & Claupein, 2013; Torralba, Fagerholm, Burgess, Moreno, & Plieninger, 2016). Soil biota could also be favoured by a greater availability and diversity of soil organic matter in the intercropping system than in woody monocultures. The spare of ploughing in nearly half the total cropping area, and the light plow used, may help reinforce the preservation of soil biota.

The distribution of crop systems among land qualities, and the fact that most landowners had a significant share of their cropland under polyculture, suggest that there could have been some facilitation process related to the soils where vines were cultivated, which were usually sloped lands and deforested soils. Additionally, cereals could be helpful for avoiding the relatively high soil erosion in vineyards (García-Ruiz, 2010; Garcia et al., 2018; Ruiz-Colmenero, Bienes, & Marques, 2011).

All these agroecological processes of niche differentiation and mutual facilitation, pest protection and soil erosion prevention could have played a role and help explain the persistence of the more diversified polycultural systems until the mid-20th century. More research is needed to specify the relative role of each of these agroecology factors and of their possible mutual synergies in different site-specific contexts and poly-cultural systems (Vandermeer, 1989).

6.2. Socioeconomic dimension

The results obtained also give us some insights about the socioeconomic rationality propelling the expansion of the alley cropping of vines and cereals. As peasant studies theories have argued (Chayanov, 1966; Van der Ploeg, 2013), traditional farmers make their decisions trying to balance different elements of their production process, regarding the achievement of an even allocation of family labour and a constant income in the long term, rather than the maximization of profits in the short term. Thus, if in land productivity terms there was no clear advantage of the intercropping system over the respective monocultures, it is possible to defend that there were other socioeconomic and cultural reasons that favoured the adoption, spread and long-term maintenance of the silvoarable system.

Risk diversification has usually been argued to be the main reason behind the cultivation of multiple crops by traditional farmers, as for example in the traditional common land (McCloskey, 1989, 1991). This could be the case in Les Oluges, where adverse climate effects and variable rainfall patterns and drought frequently damaged harvest. However, diversification of risks would not necessarily lead to the cultivation of different crops in the same plot, as in the silvoarable system, since the same risk avoidance could be obtained from cultivating different crops in different pieces of land scattered across different parts of the municipality. The question of risk diversification in the intercropping systems is mainly related to a more diversified use of soil resources. In case of a bad year or a total failure of one of the crops, these resources could still be in place.

Certainly, the expansion of vine cultivation from the mid-19th century was a response to the market boom of this crop. Then, the question would be why cereals were kept intercropped between the vines as it was already done during the previous centuries in the Segarra County (Tello, 1986, 1995). The answer could be linked to the hard agricultural conditions of Les Oluges and the low productivity of its cropland, and to the efforts of balancing and making the best use of scarce resources such as human labour and animal work.

On the one hand, the silvoarable system that combined cereals and vines allowed savings in the most expensive tasks, such as ploughing, which required the use of a more powerful draft force –mules instead of donkeys— that were also more costly to maintain. It also allowed a more even gender distribution of agricultural tasks, increasing the use of female labour. Additionally, the more even seasonality could reduce the need to hire external workers in the periods of peak work, such as for the cereal and vine harvest. Furthermore, even though monoculture of cereals provided greater resources for satisfying the needs of draft animals, the differences in this respect between vineyard and the intercropping system were not very high, and the intercropping system was better suited for replenishing the nutrients extracted than the vineyard monocrop without the large investment of external fertilization that cereal monocultures required.

Thus, the intercropping system of cereals and vines provided a better balance between the needs of family labour allocation, animal work and feeding, and fertilizing resources than the respective monocultures. Each farming family could adapt the share of this intercropping system depending on the productive factors available, such as the family composition and labour availability, the quantity and quality of soils, and the access to animal work. However, it seems clear that the socioeconomic rationality of this silvoarable system can be better understood in terms of a peasant economy (Chayanov, 1966) and the ‘art of farming’ of the traditional peasantries rather than the fully market-oriented farmers (Van der Ploeg, 2013). The alley cropping of grains and vines was an agricultural heritage of an age-old peasant culture that considered farming as a process of balancing different production relations of agriculture: labour-consumption, people-living nature, production-reproduction, internal-external resources, and autonomy-dependence.

While the agroecological analysis supports the advantages of intercropping in the same field, most of the socioeconomic advantages of polyculture could be also obtained by applying agricultural diversification at the landscape level, with different plots cultivated with different crops not necessarily mixed in the same field. Only the saving of animal work entailed a clear socioeconomic advantage of intercropping at the plot level. This is an important finding of extending the accountancy of Land Equivalent Ratios to labour requirement through what we have named Relative Total Labour Cost.

The silvoarable system studied could also respond to other cultural values that the limited historical sources available do not reflect. One possibility is linked with the irreplaceability of agricultural resources and the different value given to agricultural crops reflected in the management practices associated to each crop system. Cereal was a subsistence crop, essential for the survival of the farming community, while wine and brandies were a secondary market-oriented cash crop. Given the reduced productivity of cropland and the high risks of crop failure due to environmental hazards, sowing cereals between the lines of vines was a strategy of agricultural intensification aimed to increase the output obtained by piece of land and achieve a better satisfaction of basic needs. Put in another way, polyculture helped peasants to better avoid marked dependence and the risk of falling into forced sales due to indebtedness (Bhaduri, 1983, 1986; Tello, 1990).

We deem that understanding the long-lasting persistence of alley cropping requires combining agroecology and socioeconomic reasons from a peasant rationality (Tello, 1986), as well as from a rural community-wide biocultural standpoint. This study has advanced some steps in this direction by applying for the first time to past historical sources the Land Equivalent Ratios, and extending its use to the Relative Total Labour Cost. More research is needed to go deeper in this research from a biocultural heritage point of view (Altieri & Koohafkan, 2017).

7. Conclusions

The long-term historical evolution of the alley cropping of cereals and vines observed in Les Oluges village, with the spread of this polyculture system in the mid-19th century, and its diversification in the mid-20th century, until its complete disappearance by the end of the last century, highlights the biocultural adaptability and resilience of this kind of traditional intercropping systems. The analysis carried out has revealed some of the possible advantages of this type of diversified and multifunctional farming. It has tried to disentangle the rationality of that mixed crop system in the second half of the 19th century, but the relevance of the methods used and results obtained are not restricted to this particular place and time. They open the way for more research needed to recover from the oblivion many other types of Mediterranean traditional polycultures.

The value of this kind of historical agroecology studies goes beyond the limited scope of the local results obtained. It highlights the relevance of a traditional poly-cultural practice of which records are scarce, despite having been quite widespread before the massive adoption of the Green Revolution. Additionally, it provides a multidimensional agro-ecological and socioeconomic analysis needed to comprehend the complexity of the functioning of peasant traditional ways of farming. Furthermore, recovering and emphasizing the advantages of forgotten polycultures can provide useful knowledge to increase the multifunctionality and resilience of current agricultural systems worldwide, challenging the modern unsustainability of industrialized agriculture.

Apendix to Chapter 4: Extended results.

This Annex includes more detailed account of the results obtained for all the crop systems recorded in the local agricultural survey (*Cartilla evaluatoria*) of Les Oluges.

1. *Land Equivalent Ratio (LER)*

The Land Equivalent Ratio (LER) was obtained from the estimation of the energy content of the total produce of the crop systems. The total produce includes the main produce and the by-products of the crops systems. The LER is the sum of the relative yields, which are calculated as the yield of the polyculture divided by the yield of the monoculture. All these steps are shown in Table 21.

Table 21. Total produce, relative yields and Land Equivalent Ratio (LER) of the crop systems registered in the local agricultural survey of Les Oluges (1883) (1Q: first quality soil; 2Q: second quality soil; 3Q: third quality soil). Source: Our own, from the sources detailed in the text.

Crop systems		**Total produce (kg/ha dry matter)**			**Relative yields**			**LER**		
		1Q	**2Q**	**3Q**	**1Q**	**2Q**	**3Q**	**1Q**	**2Q**	**3Q**
Wheat		848								
Barley			1,187							
Rye				720						
Vines		3,311	2,748	1,996						
Olives		2,090	1,571	1,104						
Vines & olives	Vines	1,749	1,374	998	0.53	0.50	0.50	1.05	1.07	0.98
	Olives	1,097	889	526	0.52	0.57	0.48			
Cereals & vines	Cereals	424	593	339	0.50	0.50	0.47	0.97	1.00	0.97
	Vines	1,562	1,374	998	0.47	0.50	0.50			
Cereals & olives	Cereals	424	593	339	0.50	0.50	0.47	1.02	1.00	0.90
	Olives	1,097	785	474	0.52	0.50	0.43			
Cereals, vines & olives	Cereals	424	593	339	0.50	0.50	0.47	1.08	1.07	1.09
	Vines	1,056	869	720	0.32	0.32	0.36			
	Olives	548	393	289	0.26	0.25	0.26			

2. *Relative Total Labour Cost*

The Relative Total Labour Cost was estimated following the same methodology of the LER, in this case using the number of days of work required for each crop system (Table 22) and the monetary cost of this labour invested (Table 23), recorded in the *Cartilla evaluatoria.*

Table 22. Total labour cost and Relative Total Labour Cost, in number of days required, of the crop systems of Les Oluges (1Q: first quality soil; 2Q: second quality soil; 3Q: third quality soil). Source: Our own, from the sources detailed in the text.

Crop systems		**Total labour cost (days/ha)**			**Relative Total Labour Cost**		
		1Q	**2Q**	**3Q**	**1Q**	**2Q**	**3Q**
Wheat		21.10					
Barley			14.82				
Rye				14.64			
Vines		51.11	40.01	26.64			
Olives		55.81	40.99	27.33			
Vines & olives	Vines	19.60	17.23	11.08	1.07	1.03	0.95
	Olives	38.08	24.71	14.53			
Cereals & vines	Cereals	11.87	9.40	7.67	1.10	1.05	1.00
	Vines	27.68	16.56	12.56			
Cereals & olives	Cereals	11.87	9.40	7.67	1.30	1.23	0.96
	Olives	41.28	24.39	12.02			
Cereals, vines & olives	Cereals	11.87	9.40	7.67	1.30	1.31	1.37
	Vines	19.98	15.51	12.33			
	Olives	19.62	11.99	10.58			

Table 23. Total labour cost and Relative Total Labour Cost, in monetary cost, of the crop systems of Les Oluges (1Q: first quality soil; 2Q: second quality soil; 3Q: third quality soil). Source: Our own, from the sources detailed in the text.

Les Oluges 1860		**Total labour cost (pesetas/ha)**			**Relative Total Labour Cost**		
		1Q	**2Q**	**3Q**	**1Q**	**2Q**	**3Q**
Wheat		77.95					
Barley			56.38				
Rye				56.03			
Vines		132.46	110.25	83.51			
Olives		125.58	91.28	68.60			
Vines & olives	Vines	55.49	46.09	30.30	1.01	0.98	0.84
	Olives	73.84	51.74	32.56			
Cereals & vines	Cereals	52.16	39.30	32.65	1.07	1.02	0.91
	Vines	53.03	35.44	27.45			
Cereals & olives	Cereals	36.23	28.25	24.51	0.97	0.95	0.77
	Olives	63.95	40.64	22.49			
Cereals, vines & olives	Cereals	36.23	28.25	24.51	0.99	1.00	0.97
	Vines	37.04	29.85	23.50			
	Olives	31.10	20.49	17.09			

Additionally, for the assessment of labour seasonality, the days of work required by each crop system were grouped by season (Table 24).

Table 24. Number of days of work required by season in each crop system in Les Oluges (1Q: first quality soil; 2Q: second quality soil; 3Q: third quality soil). Source: Our own, from the sources detailed in the text.

Working days by season	**Spring**	**Summer**	**Autumn**	**Winter**	**Standard Deviation**
Wheat	0.97	7.33	6.93	3.26	3.05
Barley	0.58	5.12	4.99	3.26	2.11
Rye	0.58	4.94	4.99	3.26	2.07
Vines 1Q	23.38	0.00	27.73	0.00	14.86
Vines 2Q	21.05	0.00	18.95	0.00	11.58
Vines 3Q	16.69	0.00	9.94	0.00	8.17
Olives 1Q	20.93	0.00	16.28	18.60	9.49
Olives 2Q	15.70	0.00	11.63	13.66	7.03
Olives 3Q	12.21	0.00	6.98	8.14	5.08
Vines & olives 1Q	25.06	0.00	21.06	14.83	11.00
Vines & olives 2Q	20.41	0.00	15.78	9.01	8.87
Vines & olives 3Q	13.43	0.00	10.50	4.94	5.96
Wheat & vines	16.46	6.92	16.16	0.00	7.94
Barley & vines	12.23	4.90	8.83	0.00	5.26
Rye & vines	9.46	4.19	6.59	0.00	4.00
Wheat & olives	13.37	6.92	15.70	17.15	4.52
Barley & olives	10.08	4.90	9.69	9.13	2.40
Rye & olives	5.62	4.19	5.62	4.27	0.81
Wheat, vines & olives	17.79	6.92	18.60	8.14	6.19
Barley, vines & olives	14.09	4.90	13.55	4.36	5.32
Rye, vines & olives	11.09	4.19	11.53	3.78	4.24

3. *Energy efficiency and nutrient balances*

For the estimation of the energy flows the following assumptions were made:

3.1. Draft animal

It considers the requirements of one donkey (the most abundant draft animal in 1860) throughout a year. Its feed is provided by: *i*) crop system by-products (straw, vine leaves, olive tree browsing), and *ii*) external feed (straw) needed to complete the animal needs. Only cereal monocultures include the possibility of pasture in the fallow land, since the historical records state that pasturing in the cropland were woody crops are grown could be harmful for the perennials.

3.2. Soil distribution

The distribution of cereals by soil quality, as registered in the *Cartilla evaluatoria* is: wheat in first quality, barley in second quality and rye in third quality. This distribution applies for cereal monocultures and polycultures. Reflecting the practice of fallow every other year, half of the cereal of cropland is considered to be left fallow in monocultures and polycultures.

In polycultures that include two different crops, half of the land is used for one crop, and the other half for the other crop. In the polyculture that includes cereals, vines and olives, soil distribution includes 25% of the land sown with cereals, 25% fallow, 25% cultivated with vines and 25% cultivated with olives.

3.3. Energy flows

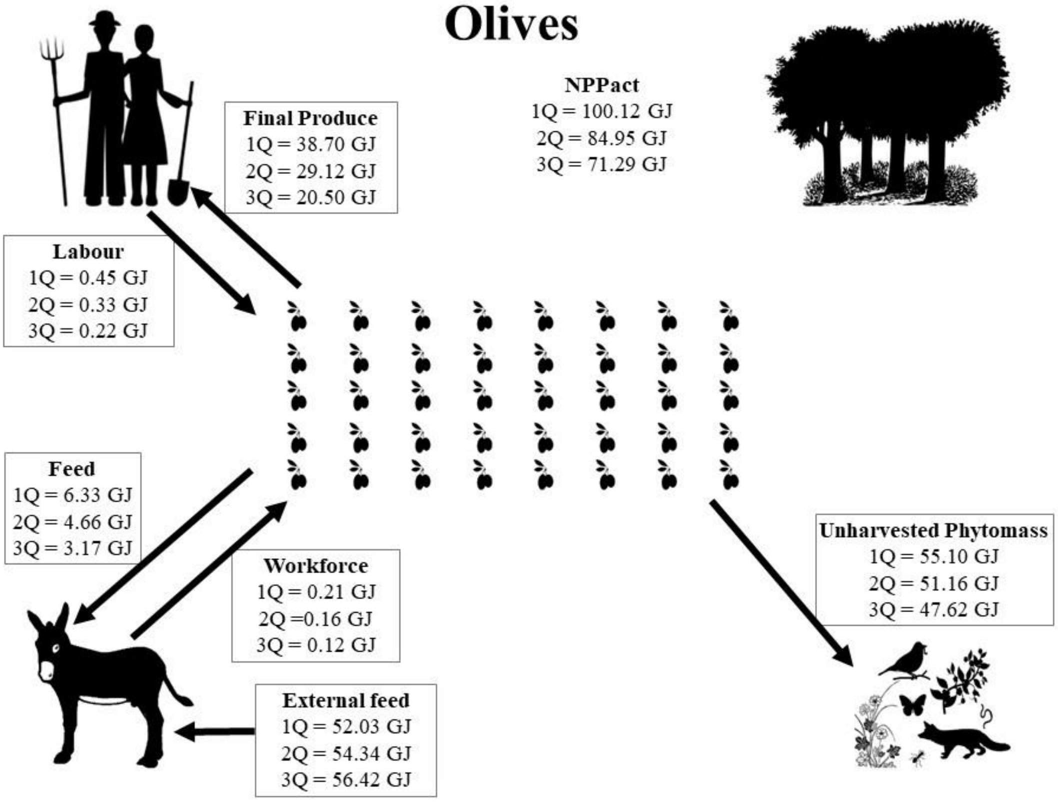
NPP is the sum of the Total Produce and the Unharvested Phytomass. The Total Produce (TP) includes the main produce and the by-products of cropland. Unharvested Phytomass (UhP) includes adventitious herbs, wild animal intake, and roots.

Final Produce (FP) includes the main produce and the by-products that are available for human use after recycling those available for animal feed and fertilization.

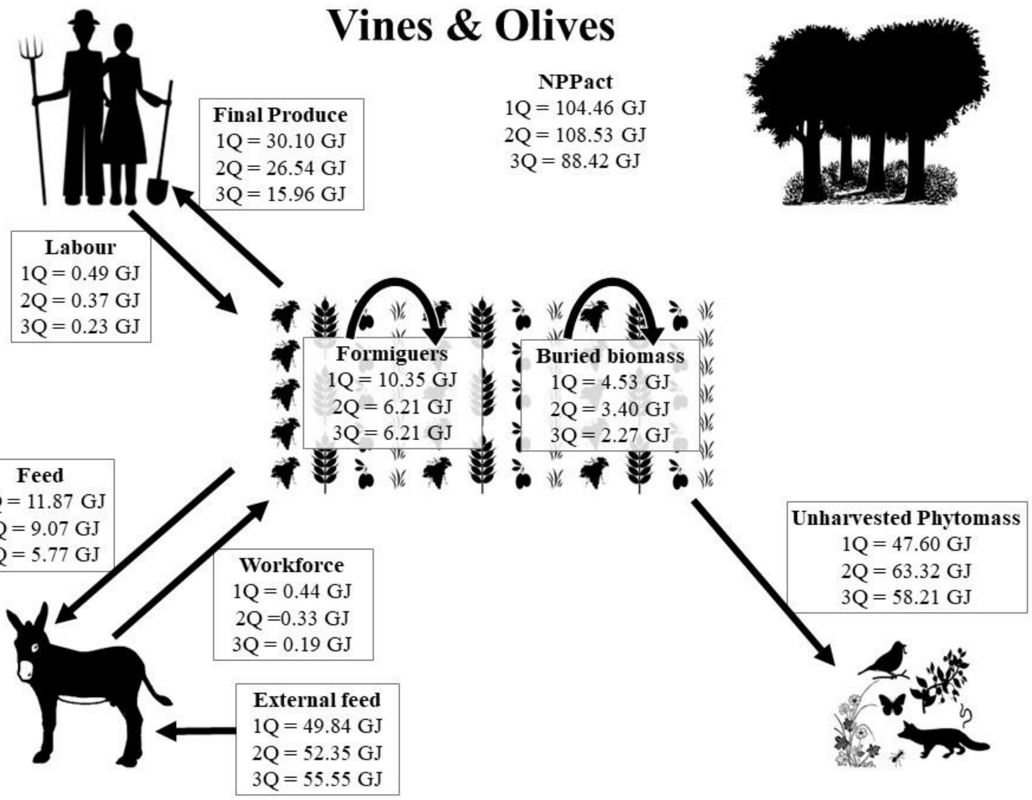
The Total Inputs Consumed (TIC) include the biomass that is recycled from the same cropland for animal feed, seeds and fertilization (buried biomass and *formiguers*), as well as external inputs of biomass such as the wood from woodland and the external animal feed needed (measured as the equivalent of the deficit of metabolizable energy of feed considered in cereal straw). However, given the high energy content of the manure applied in cereal monocultures, in this crop system the TIC consider the energy content of manure and the energy content of the animal work, and do not include the energy content of animal feed in order to avoid double counting. The number of *formiguers* built in one hectare of vineyard and cereal monocultures were 93 in first quality soil, and 56 in second and third quality soils. However, given the existence of fallow in cereals, this amount is divided by two in cereal monocultures. Similarly, in the intercropping systems that included vines, the number of *formiguers* built is accounted proportional to the share of cropland occupied by the vines. *Formiguers* in cereal monocultures are assumed to be built with wood from woodland and are thus external inputs from the plot boundaries standpoint. In vines, *formiguers* are assumed to be built with the wood available from vine pruning and strain replacement, and are thus considered biomass reused.

Figure 14.Scheme of the energy fluxes of the crop systems from Les Oluges that have not been included in the main text (1Q: first quality soil; 2Q: second quality soil; 3Q: third quality soil; W&O: wheat and olive trees; B&O: barley and olive trees; R&O: rye and olive trees; WV&O: wheat, vines and olive trees; BV&O: barley, vines and olive trees; RV&O: rye, vines and olive trees). Source: Our own, from the sources detailed in the text.

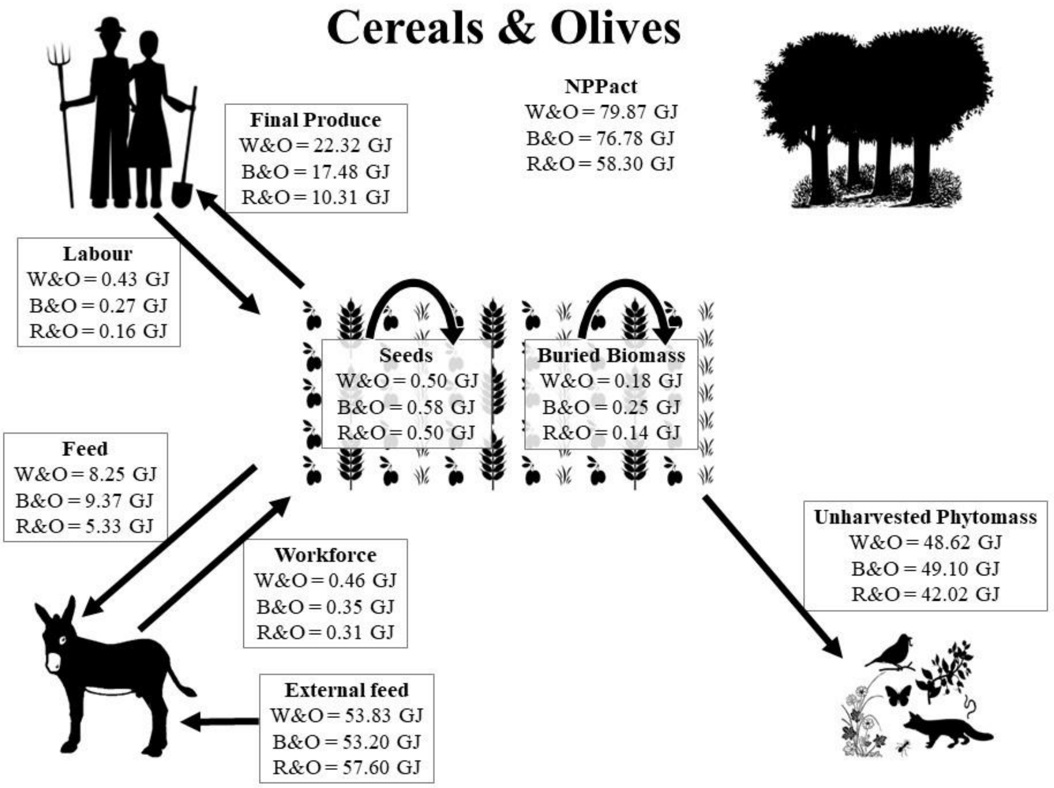
14a)



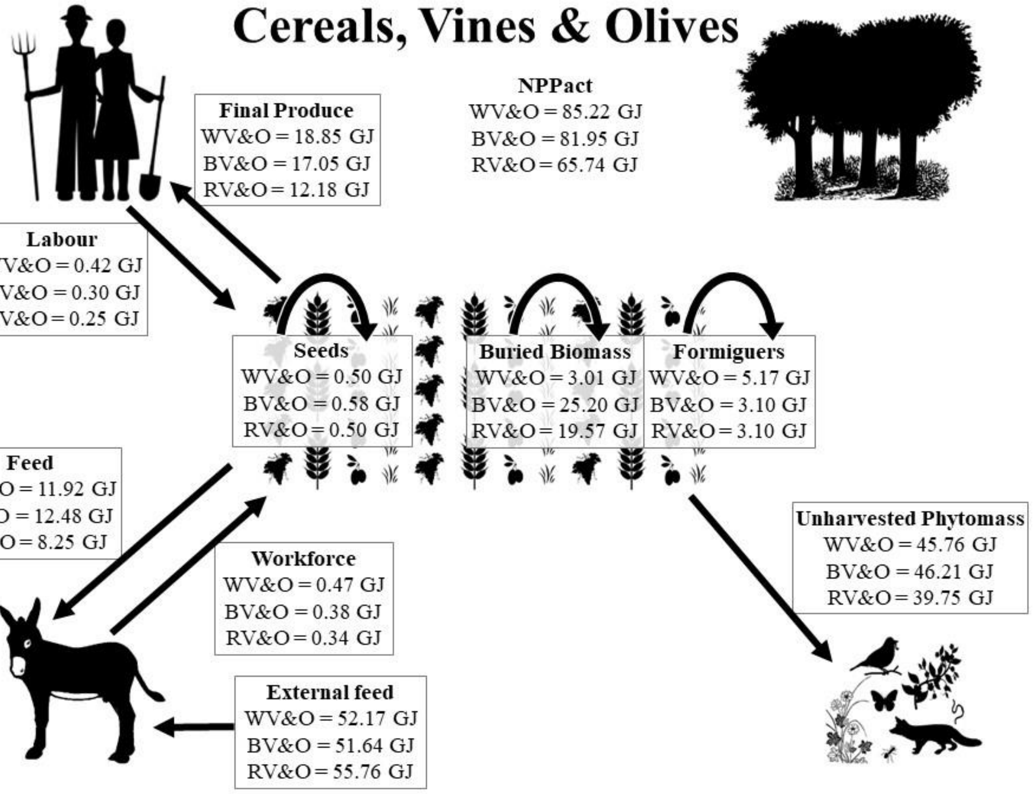
14b)


Vines & Olives
NPPact
1Q = 104.46 GJ
2Q = 108.53 GJ
3Q = 88.42 GJ
Final Produce
1Q = 30.10 GJ
2Q = 26.54 GJ
3Q = 15.96 GJ
Labour
1Q = 0.49 GJ
2Q = 0.37 GJ
3Q = 0.23 GJ
Formiguers
1Q = 10.35 GJ
2Q = 6.21 GJ
3Q = 6.21 GJ
Buried biomass
1Q = 4.53 GJ
2Q = 3.40 GJ
3Q = 2.27 GJ
Feed
1Q = 11.87 GJ
2Q = 9.07 GJ
3Q = 5.77 GJ
Workforce
1Q = 0.44 GJ
2Q =0.33 GJ
3Q = 0.19 GJ
Unharvested Phytomass
1Q = 47.60 GJ
2Q = 63.32 GJ
3Q = 58.21 GJ
External feed
1Q = 49.84 GJ
2Q = 52.35 GJ
3Q = 55.55 GJ

14c)


Cereals & Olives
NPPact
W&O = 79.87 GJ
B&O = 76.78 GJ
R&O = 58.30 GJ
Final Produce
W&O = 22.32 GJ
B&O = 17.48 GJ
R&O = 10.31 GJ
Labour
W&O = 0.43 GJ
B&O = 0.27 GJ
R&O = 0.16 GJ
Seeds
W&O = 0.50 GJ
B&O = 0.58 GJ
R&O = 0.50 GJ
Buried Biomass
W&O = 0.18 GJ
B&O = 0.25 GJ
R&O = 0.14 GJ
Feed
W&O = 8.25 GJ
B&O = 9.37 GJ
R&O = 5.33 GJ
Workforce
W&O = 0.46 GJ
B&O = 0.35 GJ
R&O = 0.31 GJ
Unharvested Phytomass
W&O = 48.62 GJ
B&O = 49.10 GJ
R&O = 42.02 GJ
External feed
W&O = 53.83 GJ
B&O = 53.20 GJ
R&O = 57.60 GJ

14d)



The distribution of the total energy produced in each crop system (NPP_{act}) among the different uses and energy flows considered in presented in Table 25, and Table 26 shows the results of the EROIS for all the crop systems of the *Cartilla evaluatoria* of Les Oluges.

Table 25. Distribution of the NPP_{act} according to the energy flows of each crop system. Source: Our own, from the sources detailed in the text.

Crop systems		**NPP_{act} distribution**			
		Unharvested Phytomass	**Final Produce**	**Animal feed**	**Recycling (seeds and fertilization)**
Wheat		55%	8%	35%	2%
Barley		53%	9%	36%	2%
Rye		56%	7%	36%	2%
Vines	1Q	38%	17%	16%	29%

	2Q	40%	23%	15%	22%
	3Q	44%	18%	13%	25%
Olives	1Q	55%	39%	6%	
	2Q	60%	34%	5%	
	3Q	67%	29%	4%	
Vines & Olives	1Q	46%	29%	11%	14%
	2Q	58%	24%	8%	9%
	3Q	66%	30%	7%	10%
Wheat & vines		51%	13%	16%	20%
Barley & vines		53%	17%	17%	13%
Rye & vines		57%	13%	14%	15%
Wheat & olives		61%	28%	10%	1%
Barley & olives		64%	23%	12%	1%
Rye & olives		72%	18%	9%	1%
Wheat, vines & olives		54%	22%	14%	10%
Barley, vines & olives		56%	21%	15%	8%
Rye, vines & olives		60%	19%	13%	8%

Table 26. EROIs of all the crop systems from Les Oluges. Source: Our own, from the sources detailed in the text.

Crop systems Les Oluges 1860	**FEROI**			**AFEROI**			**BIODIVERSITY**			**NPP$_{act}$EROI**		
	1Q	**2Q**	**3Q**	**1Q**	**2Q**	**3Q**	**1Q**	**2Q**	**3Q**	**1Q**	**2Q**	**3Q**
Wheat	0.05			0.04			0.28			0.50		
Barley		0.08			0.05			0.33			0.62	
Rye			0.05			0.04			0.29			0.53
Vines	0.39	0.62	0.48	0.21	0.30	0.22	0.46	0.52	0.54	1.20	1.29	1.22
Olives	2.26	2.60	2.14	0.54	0.47	0.36	0.76	0.82	0.83	1.39	1.36	1.25
Vines & olives	1.10	1.39	1.10	0.40	0.32	0.22	0.64	0.77	0.80	1.40	1.32	1.22
Cereals & vines	0.36	0.54	0.44	0.15	0.20	0.15	0.59	0.63	0.66	1.14	1.20	1.15
Cereals & olives	2.39	1.67	1.68	0.38	0.29	0.21	0.84	0.82	0.87	1.38	1.29	1.21
Cereals, vines & olives	0.90	0.90	0.87	0.28	0.26	0.23	0.69	0.71	0.74	1.28	1.26	1.22

3.4. Nutrient balances

The nutrient balances of the crop system from Les Oluges (Table 27) have been calculated following the methodology employed and thoroughly explained in Chapter 3.

Table 27. Nutrient balances of the main macronutrients (Nitrogen (N), Phosphorus (P), and Potassium (K)) for all the crop systems from Les Oluges. Source: Our own, from the sources detailed in the text.

Nutrient balances		N/ha	P/ha	K/ha
Cereals	1ª	2.61	2.88	13.56
	2ª	1.72	2.25	8.41
	3ª	4.26	1.83	11.55
Vines	1ª	-34.12	-2.95	-17.01
	2ª	-25.76	-2.59	-14.75
	3ª	-17.52	-1.53	-9.54
Olives	1ª	-9.64	-0.37	-0.49
	2ª	-6.25	-0.25	-0.24
	3ª	-3.21	-0.15	-0.02
Vines & olives	1ª	-23.25	-1.80	-9.43
	2ª	-16.68	-1.44	-7.54
	3ª	-10.20	-0.84	-4.76
Cereals & vines	1ª	-18.45	-2.11	-9.96
	2ª	-16.03	-2.18	-11.18
	3ª	-10.12	-1.68	-6.43
Cereals & olives	1ª	-4.38	-0.87	-2.14
	2ª	-4.03	-0.94	-3.77
	3ª	-1.50	-0.94	-1.56
Cereals, vines & olives	1ª	-15.94	-1.91	-8.05
	2ª	-13.07	-1.84	-8.80
	3ª	-8.99	-1.63	-5.58

El poder sólo es realidad donde palabra y acto no se han separado,
donde las palabras no están vacías y los hechos no son brutales,
donde las palabras no se emplean para velar intenciones sino para
descubrir realidades, y los actos no se usan para violar y destruir
sino para establecer relaciones y crear nuevas realidades.

Hannah Arendt, *La condición humana*

Si entre los dedos se me escapa volando una flor
y yo la dejo que me marque el camino…

Extremoduro, *La vereda de la puerta de atrás*

Chapter 5: Conclusions and final remarks

This chapter presents the concluding remarks of the thesis. First, I will set forth the main contributions of the research that I have developed. Secondly, I will introduce some of the limitations of this work and next, I will propose further developments that could enlarge the outreach of the investigation. Finally, some last reflections will be the ending of this thesis.

1. *Main contributions of this thesis*

The historical analysis if the agroecosystem of Les Oluges has provided important insights on the sociometabolic transformations of farm systems by means of the spread of the Green Revolution. This section does not want to repeat the contributions that are already presented in Chapters 2-4, but the aim here is to highlight the most significant learnings obtained from each chapter, and how can this research, as a whole, contribute to the investigation on the sustainability of farm systems.

The research questions presented in the Introduction (p. 7) of this thesis have been answered. Chapters 2 and 3 have shown how the transition from traditional organic farming to industrialized agriculture took place in Les Oluges, the changes in the structure and functioning of the farm system, and how this transformation affected the sustainability of the agroecosystem considering the energy and nutrient balances of the three points of time studied. The drivers of the unsustainability of modern agricultural functioning are also identified: the rise of livestock density; the increased dependence on External Inputs and the abandonment of Biomass Reused, as well as the relinquishment of traditional traits such as the polyculture system with the complete homogenization of cropland monoculture. These drivers are linked to the simplification of the agroecosystem functioning and management. Thus, learning from the complexity of the disappeared intercropping system of Les Oluges is a key lesson that is obtained from this study of traditional agroecosystems.

However, further from specifically answering the research questions established at the beginning, the investigation on Les Oluges provided powerful insights that set forth important contributions for the research on sustainable farm systems.

The energy efficiency analysis deployed in Chapter 3 provided results that confirm the general trends observed in other case studies, but it also has an important peculiarity, which is the improvement of the EROIs in 1959, under a mixed organic-industrialised functioning. This result is of great interest because it shows that under certain circumstances it is possible to achieve a combination of External Inputs and Biomass Reused that can improve the productivity of the agroecosystem for human purposes while maintaining some ecological benefits. This can be especially interesting in those cases that, as Les Oluges, have tough soil and climate conditions that severely constrain cropland productivity.

The extensive use of industrial external inputs in modern agriculture causes important pollution and energy inefficiency problems. Agroecology defends that in order to build more sustainable farm systems, the dependence on external inputs needs to be reduced. However, as the case of Les Oluges in 1959 shows, this does not necessarily mean that external inputs need or should be completely eliminated. The question on the sustainable, efficient and optimal use of external inputs nowadays is about what kind of external inputs and to what extent should they be used avoiding an external dependence and internal linearity which supress the agroecosystem complexity.

The question on the volume and nature of the external inputs leads us to the contributions of the nutrient balances on Chapter 4. The belowground assessment on the transformation of the fertilization practices in Les Oluges illustrates the complexity of the agroecosystem management. Examining the accomplishment of the different soil fertility managements in each point of time from the perspective of their efficiency, adequacy and durability, is a key contribution of this PhD thesis that gives an idea of the intricacies of soil fertility and agroecosystems management. However, this multiple assessment on the nutrient balances raises an important question on the definition of sustainability. The excessive use of fertilizing resources in 1999 was clearly unsustainable, but the more levelled nutrient balances under traditional (c. 1860) and mixed organic-industrial functioning (in 1959) entail different sustainability problems: the deforestation process in 1860, and the use of non-renewable fertilizing resources in 1959. Again, with respect to the use of fertilizing resources we find a similar question to that arisen previously: what kind of fertilizing resources, and to what extent?

This issue is especially relevant given the great diversity of agroecosystems around the world and the need to adapt agricultural practices to the specific local conditions. The transition towards more sustainable farming, despite urgent, is complex and needs to be gradual in order to ensure social adaptability, and the capacity of the various agroecosystems to function under different degrees of use of external inputs should be considered and assessed.

Finally, the main contributions of Chapter 5 are twofold. The application of the LER to the historical examination of the intercropping system, and the proposal of the Relative Total Labour Cost, are analytical contributions that should be highlighted. Additionally, there is an important historiographic contribution on the recuperation and recognition of a traditional polyculture system of which little record is maintained. The combination of the agroecological and peasant economy perspectives is an effort to unveil the traditional knowledge embedded on that biocultural heirloom. Furthermore, this analysis provides support to the introduction of a different economic rationality in agricultural systems in order to enhance their sustainability.

2. *Limitations of the research*

The development of a historiographic research from a sociometabolic perspective is, probably by its very nature, subject to various sources of limitations that arise from its multi- and interdisciplinary character.

First, there is a limitation that is probably widespread on historical research. The historical sources available for the analysis of Les Oluges provided valuable information about the structure and functioning of the agroecosystem, but working with the historical sources has implied a process of critical evaluation of the sources and estimation of those data and information that was either not available or not reliable. This is a limitation that makes it necessary to remind that the reconstruction of the land use patterns, human labour and animal work application, energy and nutrient balances, and the functioning of the crop systems, do not reflect exactly how things were, but are reasonable estimations of what could have been the case. There will always remain some uncertainty in this respect that needs to be recognized, even though the results obtained correspond to a legitimate approximation that gives rise to relevant insights.

Secondly, another limitation that I consider necessary to acknowledge is the narrow case study on which this thesis has been focused. A municipality of 20 km^2 and less than two hundred inhabitants nowadays does may not seem a case study of enough relevance for a PhD thesis on agroecological transformations and sustainable agriculture. Certainly, expanding the focus with an in-depth comparative study or inserting the analysis of Les Oluges on wider transformations at the county, regional and national scale, would have reduced this narrowness. However, as explained in the introduction of this thesis, Les Oluges is a case study representative of the historical evolution of many other localities in Spain, and its analysis could provide a basis to understand what happened in other semi-arid cereal-growing Mediterranean agroecosystems.

Finally, there is a limitation of this research that has to do with the mix of disciplines that it contains. The elaboration of the nutrient balances (Chapter 3) and the agroecological analysis of the intercropping system (Chapter 4), required an incursion into an agronomic field that was completely foreign for me and for which the historical data available was scant. The help and advice of José Ramón Olarieta on this respect has been fundamental, and it is thanks to him that I have been able to develop a somewhat sound analysis in this sense.

3. Further developments and research

This PhD thesis on Les Oluges is concluded, but it has opened many paths through which it is possible to deepen and enlarge the investigation on the long-term agricultural transformations that have led us to the current unsustainability of agrifood systems. Here are some of the possible developments that this forthcoming research could follow:

i. The historical analysis of Les Oluges ends in 1999, when the adoption of the Green Revolution technological package and the industrialization of the agroecosystem were completed. As mentioned in Chapter 3, that could be considered the peak moment of the agricultural industrialization process. From then on there has been an increased environmental concern that might have reduced some traits of the industrial agroecosystem. Thus, one line of further development would be to extend the timespan of the analysis to the first decades of the 21st century (2009 and even 2019 if data were available). This could be relevant not only because it would provide an idea as to what extent the increased environmental awareness affected the agroecosystem, and if a transition towards a more sustainable farming system is already taking place; but also because it could be useful for understanding and helping that eventual transition towards sustainability and link the historical analysis with actual policy advise.

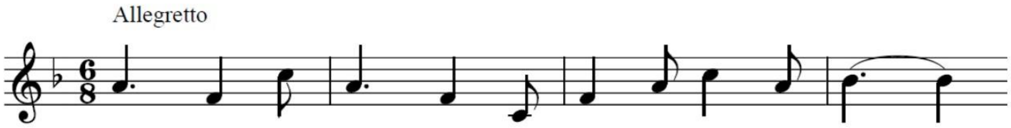
ii. There is one dimension of the sociometabolic analysis that has not been covered in this thesis: socioeconomic institutions. In order to fill this absence, a historical analysis of land property and rent distribution could be carried out. Additionally, it would also be enlightening to carry out a deeper understanding on the role that the peasant unions and cooperatives played from the beginning of the 20th century in the implementation of the Green Revolution technologies in Les Oluges. The relevance of these institutions in La Segarra has already been pointed out (Ramon Muñoz, 1998, 1999), but its linkages with the agricultural transformation experienced during the 20th century should be further studied.

iii. The research line opened in Chapter 4 with the historical analysis of Mediterranean polycultures offers several possibilities for further development. First, the possibility to develop comparative studies with similar crop systems in other regions, national and international, and in other time periods, would be helpful for clearing out the agroecological and socioeconomic advantages that silvoarable polycultures had; and it would allow to understand the contrast among different crop combinations. Secondly, even though the conclusions reached in my first attempt on this respect were not univocal, it would also be enriching to do some deeper archival research looking for more historical sources about the intercropping system that could provide an idea about why traditional farmers used this crop system, and which were the advantages perceived on combining these woody and grain crops. Finally, another line of research that falls out of the field of this thesis but that I think the historical analysis of the intercropping system could promote, is to amend the lack of historical data with the implementation of some agronomic empirical research on this type of crop systems at present. This could be useful in light of the necessary transformations that

Mediterranean agroecosystems will have to accomplish in order to adapt to a dryer and more unstable climate in the near future.

In one of the conferences on which I have presented some parts of this work, one person asked me how was this research contributing or helping to the inhabitants and farmers of the agroecosystem of Les Oluges. The aim of this thesis is not to contribute to the economic development or the well-being of Les Oluges, or not directly. As it was conceived, its contribution would be more oriented towards the academic and policy fields. However, that question made me think that the exclusively academic approach is a limitation of this research. Thus, another further development of this thesis should be to divulgate this investigation so that the people from Les Oluges can get to know there was once, someone, who spent several years of her life researching on their village, and that there is a sociometabolic interpretation of the historical transformations that Les Oluges has experienced.

4. Final remarks

I doubt whether this thesis could be considered a brick added to the construction of a sustainable socioeconomic system, or if it is rather a line in the plan of that future sustainable house. Probably, both metaphors could be applied. On the one hand, as an academic work, it has no direct tangible effects, but it helps sustain the theoretical basis, it contributes to the knowledge on how to build sustainable farm systems that could, ideally, guide future social decisions. Thus, it is certainly a line in the plan. On the other hand, the real, substantive contribution of this thesis is not that straightforward, but ultimately, it has certainly affected me, my knowledge, ideas and interests, some of my habits and my way of relating with the world have been transformed. At least, that is a small brick added to a more sustainable home and I hope that the effects of this thesis can be widen in the future. Many more steps need to be carried out and more lines need to be put together, some of them could stem and be related to this thesis, but the contribution of this research can be considered fulfilled.

Beethoven, *Symphony no. 6 Op. 68, (Pastorale). "Shepherd's song. Cheerful and thankful feelings after the storm"*

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