Socio Ecological Transition of Organic Agricultures in Catalonia (late 19th-20th century)

Elena Galán del Castillo

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Programa de Doctorat en Història Econòmica | Elena Galán del Castillo

Universitat de Barcelona

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1 

Introduction

"Whatever terrain the environmental historian chooses to investigate, he has to address the age-old predicament of how humankind can feed itself without degrading the primal source of life. Today as ever, that problem is the fundamental challenge in human ecology, and meeting it will require knowing the earth well—knowing its history and knowing its limits."

(Worster 1990)

1. The agricultural headaches of Environmental History

The dominant socio-economic and socio-technical view on industrialisation as a gradual process of continuous growth and technological change can be complemented by focusing on changes in society-nature relations (Krausmann et al. 2008). Hence, by focusing on the mode of appropriation of energy, three Socio-Ecological regimes can be described throughout human history (Sieferle 2001). These are uncontrolled solar energy use (hunter-gatherer societies), controlled solar energy use (agrarian societies) and fossil energy use (industrial societies). The periods of change between them are usually referred to as revolutions, although thinking of them in terms of Socio-Ecological Transitions provides more analysis potential (Krausmann et al. 2008; González de Molina 2010; Krausmann and Fischer-Kowalski 2013; Infante-Amate and González de Molina 2013).

In hunter-gatherer and agrarian societies—always using Siefele (2001) conceptualisation—, the supply of energy was ultimately restricted to its solar energy catchment area. Agrarian societies could increase the biomass extracted per unit of land by augmenting its human labour and draught force, but only to find eventually their 'solar' ceilings. Industrialisation is the only Socio-Ecological regime that decoupled the supply of energy from land and human labour restrictions by increasing the use of fossil fuels—first coal and later oil—(Krausmann et al. 2008). The industrialisation of agriculture reduced the area and the labour needed to increase yields (Krausmann and Haberl 2002; Krausmann et al. 2003).

The narrative of Socio-Ecological Transitions applied to Agrarian Metabolism purposed by González de Molina (2010) is focused on fertility. He divides the transition towards an industrial regime in agriculture into three waves or stages. The first wave entailed increasing the biomass production of the agroecosystems.

The spread of synthetic fertilisers allowing for an increase in yields, leaping over the restrictions of locally produced biomass characterised in the second wave. Finally, the third wave corresponds to the substitution of human labour by fossil fuel based processes through machines. This approach allows a framework of analysis of the evolution of agriculture within the perspective of Environmental History by studying the flows of energy and nutrients. Therefore, in terms of bio-physical indicators these modern increases in yields have been also associated with a decline of the energy return on investment and on a rupture in nutrient cycles. This has been the result of the concentration of intensive cropland farming and animal husbandry (Foster 1999; Moore 2000; Krausmann et al. 2003; Haberl et al. 2004; González de Molina and Guzmán 2006; Martinez-Alier 2011).

The increasing use of fossil energy and the interference of synthetic fertilisers in nutrient cycles created new environmental problems at the point of both extraction and disposal of resources. Moreover, this was accompanied with uncertainties on the endurance of the model itself as the use of stocks of fossil fuels involve only a 'temporary emancipation from land' (Mayumi 1991). To understand this, it is useful to think in terms of funds and stocks (Georgescu-Roegen 1971). If a production process is based on flows of fossil fuels, its duration depends on the depletion velocity of the limited stock. Conversely, the land is a fund whose velocity flow production simply cannot be increased. The transition towards a scenario of low availability or exhaustion of fossil fuels is not simply a matter of replacement. Renewable energy sources have lower power densities than fossil fuels and will therefore boost the demand for land (Scheidel and Sorman 2012).

In addition, this bio-physical analysis has the potentiality to show at least some part of the environmental degradation caused by agricultural practices. It has special relevance when we deal with past agricultural systems: "*Thus, the interpretation potential that offers the image projected in the physical world by the monetary version of farming systems increases with the process of "modernization"(or monetization) of itself and decreases as we move into the past. The only way to avoid this problem is to analyze the physical functioning of agricultural systems and their technical options in the most complete and realistic way, but this analysis looks mediated by its degree of economic and commercial projection.*''(Naredo 2004a).

Therefore, using bio-physical indicators and applying the concept of ecosystem to the study of agriculture is a matter for the field of Environmental History (Worster 1990; González de Molina and Toledo 2011). Also, this opens the possibilities of research and dialogues with other disciplines, together with abandoning the idea of interpreting history in terms of progress (González de Molina 2000; Congost

2004; Naredo 2004b; Barca 2011). This applies specially for the comparison of industrial and organic based agricultures because during the centuries traditional farmers have developed strategies less harmful to nature and have made agroecosystems more able to deal with changing situations (Worster 1990; Altieri and Toledo 2011).

In fact, the duality of backwardness versus progress as an analytical tool has been strongly criticised by those scholars studying agrarian, rural change or peasant societies. It entails a biased simplification of reality towards a unique desirable pathway for agriculture development (Díaz-Geada 2013) (as illustrated in Figure 1). Nevertheless, this does not mean that this duality is not working in practice, a good example are the promotion of standardised agricultural practices successful in terms of increasing wealth in particular contexts that had disastrous effects in different contexts (Bernstein 1990; Borras 2003; McMichael 2008; Ariza-Montobbio and Lele 2010; White et al. 2012; Scheidel et al. 2013; van der Ploeg 2014; Mingorría et al. 2014; Ravera et al. 2014). The challenge of these views is the definition of a multidimensional framework to address land productivity, environmental interactions, food availability and wealth across scales, as the choice of one measure, e.g. money or calories may favour one type of production or another (van der Ploeg 2014).

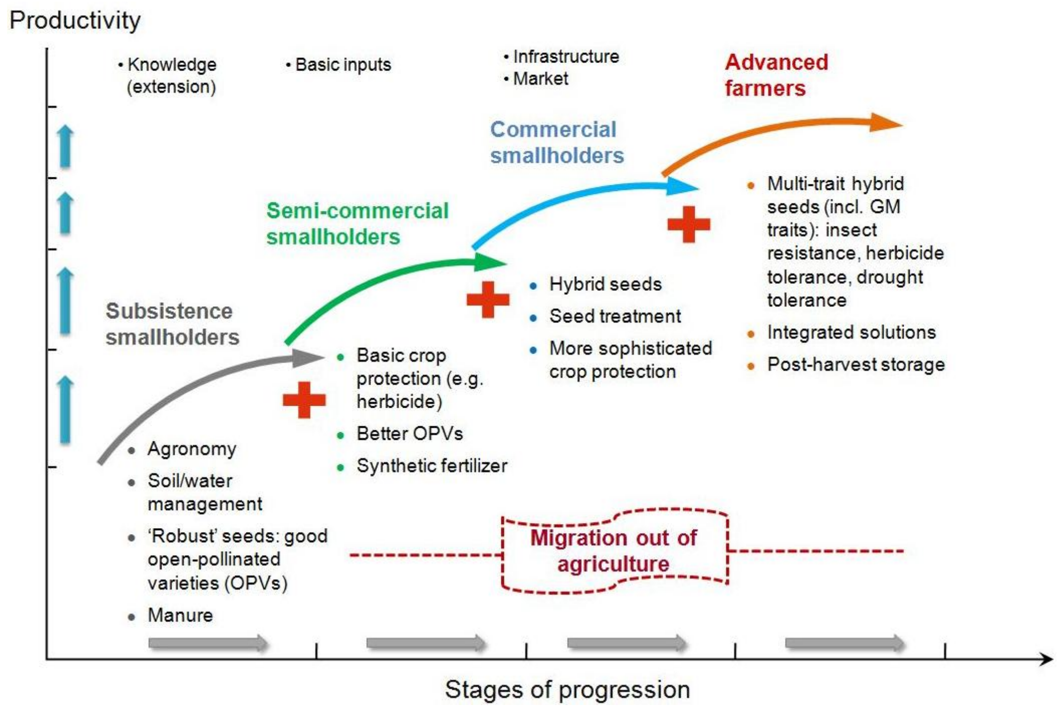

Figure 1. "Additive stages of agricultural intensification" from Zhou (2010), cited as "The imperial view of agricultural development" in van der Ploeg (2014). This figure exemplifies in a broad sense the vision of a unique trajectory of agriculture as a condition to get productivity rises.

Source: from Zhou (2010), reproduced with the permission of Syngenta Foundation for Sustainable Agriculture (SFSA).

History does not have a determinate direction, nor do the use of energy and materials, therefore Environmental History seeks its meaning by building a discourse around sustainability (González de Molina and Toledo 2011). To study this social metabolism, there is a series of tools that include bio-physical indicators widely used in Ecological Economics field such as human appropriation of net primary production (HANPP), the ecological footprint, and the energy output/input ratio (or EROI) (Martinez-Alier and Schandl 2002). Moreover, the historical point of view offers information about the responses of societies to key events, and the effects of these responses (Paavola and Fraser 2011).

We intend to follow Naredo's criticism addressed to the mainstream economic analysis based on a production function accounted only in monetary values. This criticism also shares the view put forward by several agrarian and environmental historians who have recently challenged the "backwardness paradigm" of Spanish agriculture, explained below. They adopted an Ecological Economics and Agro-ecological approach, bringing into light the role played by the environmental endowment that framed the actual frontier of agronomic possibilities of agricultural improvement (Pujol-Andreu et al. 2001).

This approach does not deny that economic incentives, technical changes, agrarian class structures, institutional settings, social conflicts and public policies also played a role as determinants of historical paths followed by the Spanish agricultural systems from the 1860s to the mid-twentieth century. In that sense, our results will need to be combined with other perspectives and different data to be able to explain the overall economic history of north-eastern Spanish agriculture in the period analysed, as it is the case in recent textbooks or readings of that subject (Federico 2005; Lains and Pinilla 2008). The same applies to the consideration of sustainability. However we defined our system, it will always be related hierarchically with other systems, and what is sustainable for one system may not be sustainable for another (Giampietro 1994; Costanza and Patten 1995).

Nevertheless, our research has a specific focus devoted to the agro-ecological reasons that were behind (if any) the end of past organic agricultural management, and its links with changing land-use patterns. It does not intend to place itself in the midst of the historiography debates of whether the economic performance of Spanish agriculture was bad or not.

2. Membership to two projects

This thesis is framed in two projects. One is an international project called "Sustainable farm systems: long-term socio-ecological metabolism in western agriculture", funded by the Social Science and Humanities Research Council of Canada. It is a Partnership Grant shared between the universities of Saskatchewan, Michigan, Alpen Adria-Klagenfurt in Vienna, Universidad Pablo de Olavide (UPO) in Seville, Barcelona, Nacional de Colombia and la Habana and Matanzas in Cuba. It aims at a comparative analysis of the transition experienced by agriculture on both sides of the Atlantic from the point of view of the interaction with natural systems through the energy and material flows moved across the landscape.

The second project is in Spain “Sistemas agrarios sustentables y transiciones en el metabolismo agrario: desigualdad social y cambios institucionales en España (1750-2010)” (HAR2012-38920-C02-02). This project is the continuation of a previous one ("Environmental History of Mediterranean Agrarian Landscapes: Origins, economic driving forces, social agents and ecological impacts of land-use change" HAR2009-13748-C03), which assembled three sub-projects at the University of Barcelona, University of Lerida and UPO. This project combines the long run approach of Social Metabolism with the analysis of social relations, trade, conflicts, institutions and landscape ecology. Social inequality appears in the headline of this project because one of the main hypotheses is that it was an issue in many agro-ecological imbalances that disrupted past organic agricultural systems, interrupted their improvement, and lead them towards industrialised agricultures based on fossil fuels.

The Spanish project has five interrelated aims:

Characterise the long-term historical processes of socio-ecological change experienced by Mediterranean agricultural systems and agrarian landscapes.

Specify their main driving forces, relating the use of energy, nutrients, water and other biophysical materials with the prevailing land-use management.

Identify the major ruling forces behind these agro-ecological changes, such as land ownership and tenure, connection with markets, labour relations, income distribution, social conflicts or public policies.

Assess the environmental impact of these land-use and land cover changes, especially from the standpoint of agro-diversity, biodiversity and resilience of cultural landscapes.

Develop new approaches and methodologies in order to highlight the relationships between the efficiency in socio-metabolic flows, land-use patterns and ecological functioning of landscapes.

To sum up, this project aims to set the pace and chronology of the three waves of Socio-Ecological Transition (SET) (Krausmann et al. 2008; González de Molina 2010) in Spanish agriculture. That is, to do a historical interpretation on the driving and ruling forces that fostered the socio-ecological transition of agricultural systems. To support this, a deep historical and trans-disciplinary analysis is needed which requires assembling a great deal of interrelated datasets.

Using the terms from the project, this thesis is focused on the driving forces. Its role is to bring information on some of the biophysical flows and to frame them within the ruling forces that evolved along the first waves of the SET in Catalonia. Then, the differential path followed by the north-eastern Spanish regions will become another specific test to be compared with the results obtained using the same methodology in other case studies in the South and North-West of Spain, in central European regions such as Austria, in the North American Great Plains, or in other American places like Cuba or Colombia. Therefore, the contribution of this thesis offers relevant results to both Spanish and international networks while at the same time benefits from the comparative outcomes of the other partners. In addition, efforts have been made to elaborate raw data so that calculations are easily replicable for other team members. .

3. Agricultural changes at the end of 19th and the beginning of 20th century

By the 1870s, the increasing efficiency of transport along with the extension of the North-American frontier and the voluntary mass migration from Europe, resulted in grain from North-America flooding European cereal markets thus lowering the price of grain (O’Rourke 2009). In the previous decades, the depletion of soil fertility through the loss of soil nutrients was of major concern in North America and Europe. That was the scenario for the origin of soil chemistry, with the publication of the first edition of Organic Chemistry in Its Applications to Agriculture and Physiology' by Liebig in 1840. These years also saw the construction of the first factory for the production of superphosphates in 1843 by the hand of the English scientist Lawes and the guano race between United Kingdom and United States (Foster 1999; Foster 2004). In this sense, the 'grain invasion' of the late nineteenth century in European and North American agroecosystems literally clashed. Old European agricultures had to deal with forced increases in productivity through highly labour-intensive methods, whereas the agriculture practiced by settlers in the New World could take advantage of the nutrients accumulated in soils along thousands of years, at least until the 1930s (Cunfer and Krausmann 2009).

In addition, the demand for dairy items of consumption like those derived from livestock and horticultural products also increased, and the characteristic degree of self-sufficiency of traditional European agricultures began to be limited by its growing dependence from markets. The reactions of European agricultures to these changes were the same as elsewhere along the twentieth and twenty-first centuries: usingthe maximum productive potential of the land, developing cash crops and decreasing production costs. In order to decrease production costs, two types of technologies were developed and/or implemented (Chorley 1981; van Zanden 1991; Arizpe et al. 2011):

a) Land-saving technologies such as the use of irrigation or chemical fertilisers. The price of additional organic manure had been rising due to the land needed to grow fodder and the human labour needed to feed cattle, collect manure and spread it on cropland. With chemical fertilisers the integration of livestock with cropland was no longer needed, and the previous 'land cost of sustainability' could be freed up (Guzmán and González de Molina 2009). According to this, the use of concentrated feeds started to grow. The use of improved bred seeds more responsive to the application of chemical fertilisers and less tending to lodge [1] (McNeill and Winiwarter 2006) was introduced within this period in Europe, although they took more time to spread to Spain (Pujol-Andreu 2011) .

b) Labour-saving technologies such as the replacement of wooden parts of agricultural implements by iron and steel. At the beginning of this period a supply of automotive power adequate enough for tillage and other tasks needed to toil the land was not implemented. Therefore, this first mechanisation of agriculture remained mainly limited to those steps of the production process that were concentrated in a place (e.g. threshing, butter-making or irrigation pumps) or combined with draught animals. These machines, e.g. reaper machines, were first developed in the United States where they had a very extensive use of land and were of a considerable size and required the use of several animals. In Europe in the first third of the twentieth century, these machines were reproduced and adapted to smaller scales suitable for a single horse or mule. As the use of fossil fuels started to spread, mechanisation was extended to other steps of the

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[1] If the nitrogen supply is excessive, the plant grows too tall and falls over (Shiel 2010)

production process, whenever possible; in order to increasingly replace livestock and human labour work.

All these changes were dependent on inputs and price fluctuations, which varied from place to place, so their spreading pattern was irregular in time and diverse in space. From a socio-metabolic perspective, this period was very interesting because it entailed the coexistence of two different ways of managing the resources of the agro-ecosystem, they were almost opposite. One based on the recirculation of energy (human labour and livestock work), nutrients and information (the peasant know-how) and the other one based on imports of fossil fuels, nutrients and information (e.g. improved bred seeds, which became increasingly appropriated by scientists and then by big enterprises).

3.1. A Spanish backward agriculture?

Whereas these technologies were implemented in Atlantic or Central Europe, and yields were increasing over all these regions—particularly the European North—, Spain remained at the bottom level of agricultural labour and land productivity in comparison with its European neighbours (van Zanden 1991; O'Brien and Prados de la Escosura 1992; Simpson 2003). Therefore, when compared to other countries, the Spanish agriculture at the end of the nineteenth century and the first half of the twentieth century used to be qualified as backward à la Gerschenkron (1962).

The fin-de-siècle agrarian crisis hit Spain strongly; not only the cheap cereals, but also the new vegetable oils and the phylloxera plague, which changed the market conditions of the markets of olive oil and wine and therefore constrained the competitiveness of Spanish agriculture (Simpson 2003). The way out of the fin-de-siècle crisis was by the combination of traditional with modern technologies, as the protectionist laws on grain went hand in hand with two apparently contradictory trends, the modernisation of exploitations—increasing land productivity— and also the ploughing of new land—decreasing land productivity (Gallego 1986). In this way, fallows coexisted with manure and synthetic fertilisers; traditional wooden ploughs coexisted with modern steel ploughs and the number of draught livestock increased. Despite this coexistence, during the first decade of the twentieth century, the Spanish agriculture stopped to be a lagging sector (Gallego 1986). After World War I, not only agriculture, but the entire Spanish economy started a transformation of growth and modernisation up to the thirties. Thereafter due to the global depression and a period of societal upheaval in Spain there was a process of degeneration in agriculture along with other sectors, which bogged down the Spanish economy (Gallego 1986).

The most important institutional factors involved with the comparatively low labour and land productivity of Spanish agriculture, were the lack of investment in irrigation systems, transportation and other services, low fiscal pressures and failures in the promotion of agrarian loans (Sudrià and Pascual 2002). Among the technical factors, were just mainly focused on increasing the cultivated land (Simpson 2003) an opinion concurred by Huguet del Villar, one of the most important Spanish geographers of the beginning of the twentieth century (Tello and Sudrià 2011). Also, it has been argued that the innovations that permitted agricultural growth in countries of the North Atlantic and Europe were ineffective with the arid or semi-arid environmental conditions, as most of the regions of Mediterranean Spain (Pujol-Andreu et al. 2001; Garrabou and Tello 2010; Santiago-Caballero 2013). Certainly, convertible husbandry and rotations including leguminous fodder crops allowed high livestock densities and therefore better integration of livestock with arable land but could not be implemented in most of Spain due to the summer droughts (Simpson 2003). Nevertheless, as the same authors argued, regional differences affecting both the institutional and the environmental dimensions should be studied, as not all Spain followed the trend of dry-farming in interior areas.

The conditions of the Mediterranean coastal areas were similar to the interior but aside fromcereals, perennial wooden crops like vineyards, olive groves and carob trees were cultivated. Catalonia, in the Northeast of the Iberian Peninsula is an interesting case, as the dynamics of interior dry-farming grain lands and specialised vineyard areas coexisted in the late nineteenth and beginning of the twentieth century. In addition, there were high differences between interior and coastal grain areas. While in the interior the yields were low, unstable and comparable to the Castilian ones, in coastal areas there were comparable to other European advanced agricultures, even fallow was almost suppressed at the end of the nineteenth century (Garrabou et al. 1995).

Likewise in most of Spain, except in the mountain and intensive irrigated areas, Catalan agriculture used high labour numbers concentrated at some moments of the year, thus creating a seasonal surplus of labour (Garrabou et al. 1992a). Pure wage labourers were almost inexistent and although a big share of rural population had access to land, the size distribution was not equilibrated. In addition, monetary rents only existed in highly profitable irrigated lands and the main mechanism to land access was through sharecropping, whose specific form in vineyard lands was the *rabassa morta* contract (Garrabou et al. 1992a). The vineyard specialisation during the nineteenth century relied on this contract. Sharecropping in Catalonia did not disappeared until the mid-twentieth century (Garrabou et al. 2001a).

Although in the mid-nineteenth century, inequality in vineyard areas was lower than in grain-specialised areas, it grew faster than elsewhere in the late nineteenth century (Badia-Miró and Tello 2014). Therefore, the effects of the fin-de-siècle crisis were more exacerbated in vineyard areas, which was expressed with high social unrest and violence at the beginning of the twentieth century (Garrabou et al. 1992b). Hence, everywhere during the period of the crisis, the rural exodus was intensified and the ones who stayed had to adapt to a new situation of increasing—but not sufficiently—salaries and low agrarian prices. In addition, wine production suffered an overproduction crises in the international market (Garrabou et al. 1992a).

For those who remained in rural societies, the way out of the fin-de-siècle crisis at the beginning of the twentieth century passed through increasing land and labour productivity together with reducing the seasonality of labour (Garrabou et al. 1992a). This was made with a change in crop types, for instance there was local specialisation in high-input crops such as oranges, rice and nuts (Calatayud 2006). Also, in the interior areas, vineyards where converted to grain areas and in the most humid areas of the northeast of Catalonia, livestock breeding started to grow (Garrabou et al. 2001a). In the grain lands of the interior, yield fluctuation was reduced (Saguer and Garrabou 1995a). Agrarian unionism, cooperatives and landowners were important stakeholders in the diffusion of industrial fertilisers at the beginning of the twentieth century in the southwest of Catalonia (Garrabou et al. 2001a). Although there were some attempts to introduce new wheat varieties (Garrabou et al. 1992a), it was not until the late twentieth century that high-yielding semi-dwarf wheat varieties were used in Spain (Pujol-Andreu 2011).

4. Focus and structure

Summing up, this thesis seeks to bring to light the ways followed by Mediterranean organic agricultures to overcome its yield ceilings (not necessary Mathusian ceilings) in order to be adapted to the structural changes of the economy explained above. It also aims to answer the question of whether there was or not a room for further organic improvements before the arrival of the second and third waves of the Socio-Ecological Transition. That is, when they finally outstripped all previous yield ceilings thanks to the spread of the use of fossil fuels, directly or indirectly in the form of chemical fertilisers, concentrated feed, and use of adapted seeds, etc.

Following the previous works in Spain of Campos and Naredo (1980), Carpintero and Naredo (2006) and González de Molina and Guzmán (2006), we are going to use the analytical perspective of the social metabolism and agro-ecology applied to Environmental History. Within the framework of the projects explained above, we are going to focus the study on the following two sets of flows.

4.1. Energy flows

Martinez-Alier and Naredo (1989) pointed out that the first study on energetic flows in agriculture was made by Podolinsky in the late nineteenth century, although in his proposal he omitted the non-labour inputs (Burkett and Foster 2006). After this first attempt, there have been important studies from time to time in the first half of the twentieth century; perhaps the most famous where the ones of the 1970s by Odum (1971), Pimentel et al. (1973) and Leach (1975). The basic finding was always the same, when comparing less industrialised agricultures with industrialised agricultures the energy efficiency declined. The increase in energy inputs was larger than the growth in the yields (Martinez-Alier 2011).

The pioneer energy analysis in Spain was made by Campos and Naredo (1980). They analyzed the energy flows of Spanish agriculture from the 1950s to the 1980s and confirmed the decreasing trend in energy efficiency. The importance of their analysis in the rebuilding of the agricultural history of Spain is that they included the metabolic approach. Hence, the bio-physical analysis of flows and balances allowed them to include the non-monetary factors influencing both marketable and non-marketable production, which were of outmost relevance in past agricultural systems (Naredo 2004a). Moreover by doing so they introduced, perhaps the first, strong scientific criticism to the industrial mode of agriculture developed under Franco's dictatorship and since. Since then, a number of Spanish historians have conducted adaptations of the Energy Flow Accounting to study past and present Spanish agricultural systems (Cussó et al. 2006a; González de Molina and Guzmán 2006; Cussó et al. 2006b; Guzmán and González de Molina 2009).

Besides energy efficiency, Energy Flow Accounting is used to calculate the amount of energy that a particular social metabolism requires for its operation. Hence providing a very graphic idea of how to articulate the various components of an agro-ecosystem in order to meet societal energy needs (Haberl et al. 2004). In addition, from the focus of Systems Ecology, the account of energy flows as information carriers of structure and organisation opens the door to relate the compatibility of agroecosystems with other subsystems (Giampietro et al. 1992a).

4.2. Nutrient flows

Fertility was of major concern in the European societies of the mid-nineteenth century. Even Marx, a contemporary observer of the changes before the grain invasion on English agriculture wrote important passages on it (Foster 1999).

Human practices can spoil or improve fertility; the practices of restoring or improving nutrients in the first horizons of the soil were embodied in agricultural produce but are not necessarily reflected in the price of agricultural commodities. In the same way as reproducing costs of human labour is not included in wages (Burkett 1999; Foster 2004; Olarieta et al. 2008). Beyond the intial definition of social metabolism processes (Marx 1976), it has to do not only with the creation of value (measured in monetary terms), but with the extraction and restoration of environmental and social value (Foster 2004). Hence, the metabolic rift in agriculture was created by the interruption of the recycling processes of organic matter.

First by the polarisation between rural and urban environments, which increased the trade distance of food and clothing resulting in fertility problems of the former and "waste" problems of the latter. And later, the rift was widened by confinement of livestock breeding, thus exacerbating waste problems and the spread of synthetic fertilisers together with the cultivars responding to them, which resolved partially and temporally the issue of fertility (Foster 1999). According to Moore (2000) this is a process that started in the XVI century and which was accelerated (instead of been solved by technology) with the spread of the wide industrialisation of agriculture from the XIX century onwards. Both authors coincide, pointing out that the solutions to problems created by the metabolic rift are not by means of technology, but by the change in social relations (Foster 1999; Moore 2000). In fact, the knowledge about the importance of recycling of organic matter already existed (Marald 2002).

Some authors have criticised this view of being anchored in the nineteenth century knowledge of agronomy and in Marx's argument of urban-rural polarisation (Schneider and McMichael 2010). According to them, the analyses of Marx lacks an accountancy proving the applications of human excrements were the cornerstone is to balance the nutrients in agricultural soils of the time. Schneider and McMichael (2010) argued that the use of human excrements would have not been enough to maintain soil fertility, as important losses may occur in the process to return organic matter to the fields. Other practices embodied in the knowledge of farmers, the existence of other lands to extract nutrients from and to maintain ecological processes were needed to cultivate in both socially and ecologically sustainable ways (Guzmán and González de Molina 2009; Schneider and McMichael 2010). In addition, it has been demonstrated that fertility is not just a function of the additions of one single nutrient. The addition of synthetic fertilisers incurs diminishing returns as further applications are not so effective in increasing yields (Tilman et al. 2002). Besides the chemical balance of main macronutrients, the physical condition of soil and soil health are also essential aspects of fertility (Doran 2002; Manlay et al. 2007; Feller et al. 2012).

Understanding that fertility of cropland areas is the result of the complex interaction of material and the intangible spheres of societies and natures, we took the balance between the flows of nutrients extracted and returned to cropland areas as a proxy of the maintenance of fertility. At least, the fertilising methods and other agricultural practices embed the information flows that configure the agroecosystem (González de Molina and Toledo 2011). Moreover, recent methodology has been developed to deal with nutrient balances of agroecosystems using historical data (Garcia-Ruiz et al. 2012). In order to assess the fertilising management from a nutrients cycling perspective, the objective of the balance is to highlight the key role played by reuses and detect whether there was or not a soil mining of nutrients.

Finally, the thesis is organised in the following structure. In the first block we make an analytical proposal to study and compare different energy efficiencies of agroecosystems and we apply it to a case study in the centre of Catalonia c.1860 and in 1999 (chapter 1 and 2). The second block is centred on the nutrient balances of the cropland areas of Catalan agriculture, hence, chapters 4 and 5 show two moments of time, c.1860 and c.1920. While chapter 4 analyses one municipality (Sentmenat) chapter 5 makes a regional analysis thus using provincial sources. This allows for the comparison among regions with different features. In the last chapter (3 and 6) of both blocks, we clarify the relations between the two chapters of each block, making joined questions and conclusions. In addition, we interpret the results in the framework of Socio-Ecological Transitions and explore the limitations of the methodology. Finally, in chapter 7 we summarize the conclusions of both blocks.

Bloc 1. Energy flows

Chapter 1. The Energy Return On Investment (EROI) in agroecosystems: An analytical proposal to study socioecological transitions to industrialized farm systems (the Vallès County, Catalonia, c.1860 and 1999)[1]

1. Introduction

Energy analysis of farm systemshas a long tradition (e.g.Pelletier et al. 2011)and is an important approach in thesustainability assessment of agroecosystems. Analysing the transformation ratios yielded by agroecosystems capable of providing more energy carriers than the ones spent in producing them may revealusefulways to improve the energy performance of industrialized agricultural systems which are usually energy sinks at present(Odum 1984). This is a relevant task at a time when long-term global food security is at stake, since agriculture is now dependent on fossil fuels even as the world faces peak oil, decreasing energy returnsinoil extraction and delivery, and climate change (Murphy and Hall 2011; Arizpe et al. 2011; Hall 2011; Scheidel and Sorman 2012; Giampietro et al. 2013).

After many decades of energy analyses of farm systems a range of different approaches and measures of energy returns are available, each calculated adopting different system boundaries and accountancy rules. Although it hampers comparability of results,this plurality of assessments is not a sign of sloppy science but rather a reflection of the epistemological challenges faced by science when dealing with a complex, hierarchical reality (Giampietro and Mayumi 2000). Different standpoints place system boundaries differently and leadtodifferent measures of energy performance that retain their own meaning within the analytical entryway adopted.The only workable way to deal with this unavoidable complexity is to compile in a transparent way a set of different energy approaches and protocolsso that researchers could understand each other and benefit from their achievements (Mulder and Hagens 2008; Murphy et al. 2011).

[1]This paper was coauthored by E. Tello, V. Sacristán, G. Cunfer, G.I. Guzmán, M. González de Molina, F. Krausmann, S. Gingrich, R. Padró, I. Marco, D. Moreno-Delgado. My contributions were the original idea, rebuilding all the calculations of the case studies together with I. Marco and R. Padró, participating actively in the construction of the model, searching and discussing references and the writing of the paper.

Being a purpose-oriented and site-specific account, the first step for any energy analysis is to make clear what we are looking to use this accountancy for(Jones 1989).Our approach aims to open a door for further studies linking energy accounting of the agroecosystem functioning with the complexity of landscape patterns and processes, and the biodiversity it may host.This means placing the system boundaries to define the agroecosystem limits, and adopting the standpoint of the people that operate it.This energy analysis is addressed to a sustainability assessment of farm systems—that is, to what extent the agroecosystem functioning yields a final produce while the underlying funds that maintain soil fertility and provide biodiversity services are maintained, enhanced or degraded (Costanza and Patten 1995).

Following this cyclical view of the sustainable functioning of farm systems, wepresent a workable proposal to the energy accountancy of agroecosystems that is exemplified with five Catalan municipalities circa 1860 and in 1999.After having recalculated all the data previously published by (Cussó et al. 2006a; Cussó et al. 2006b)for this case study, following the criteria and methods proposed in this paper, we considered how this approach to the agroecosystem functioning can be expressed with the ratio of Energy Return On Investment (EROI) that compares a system’s energy input to its energy output(Costanza 2013). We end using four EROIs linkedto one another asa way to provide a wider energy profile of agroecosystems aimed to allow comparingdifferent farm systems alongSocio-EcologicalTransitions (González de Molina 2010; Krausmann and Fischer-Kowalski 2013).

In next section 2 we explainthisagroecosystem approach to energy analysis, our conceptual system boundaries, the methodology followed to account for human labour, and the relation we deem to exist between unharvested and reused biomass with landscape patterns and biodiversity. In section 3we present the four EROI proposed and the ways to interrelate them. Section 4 discusses the results found in the Catalan examples of organic and industrial farm systems used as examples. Finally, section 5 outlines some general conclusions and perspectives for forthcoming research.

2. Analytical approach

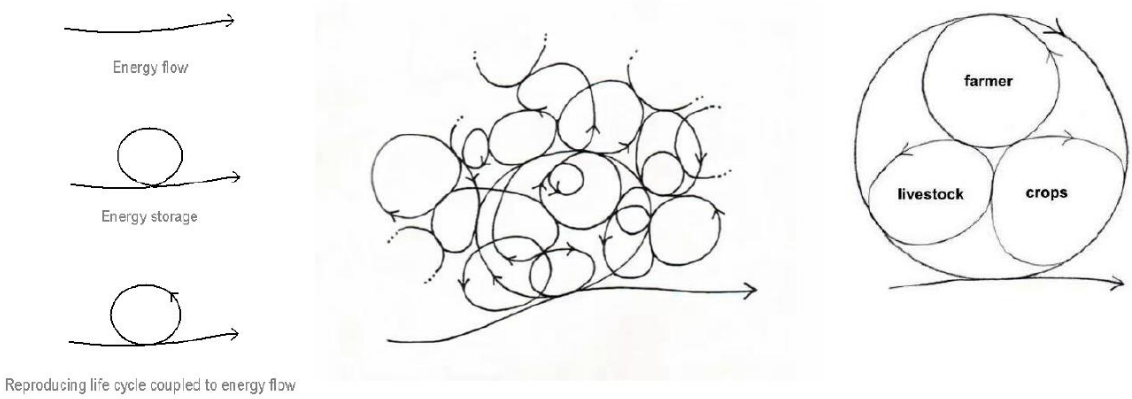
2.1. From ecosystems to agroecosystems

Agroecosystems are hybrid human-natural systems thatrequire aspecific entrywaywhen assessing EROIs. When farm operators invest human labour, animal or mechanical work, seeds, fertilisers and other energy carriers they create a new cultural landscape from the existing ecosystem(Odum 2007). As human-colonized ecosystems,agroecosystemsretain their own ecological processesbut cannot maintain and replicate themselves through time. Their maintenance requires continuous investment of energy and information by human society, in addition to ecosystem services—even though after the industrialisation of agriculture humans have tried to reduce the significance of uncontrolled ecosystem services replacing them by agrochemicals and other fossil fuel based technology(Gliessman 1998; Altieri and Nicholls 2005; Snapp and Pound 2008).

The human appropriation, transformation, use, consumption and excretion of the Net Primary Production (NPP) of agroecosystemsentail an ecological disturbance that may lead either to improvement or degradation of for instance soil fertility and biodiversity. Whether such appropriation damages natural systems depends on the resilience of the transformed ecosystem, and the density or shape of human-driven energy and material throughputs (Giampietro 2003). In order to analyse this coupled socio-ecological metabolism we have to start looking at humans as being components of ecosystems (McDonnell and Pickett 1993)as well as agroecosystems as nature transformed by humans (Haberl et al. 2004; González de Molina and Toledo 2011).

Our standpoint ultimately draws on some basic principles of the functioning of any kind of living system able to maintain a dynamic stability far from thermodynamic equilibrium. The internal cycles always make thermodynamic sense because thanks to them a living system can enhance its own complexity, increase its energy storage capacity, improve the energy throughput and start an ascendancy trend that decreases entropy dissipation thus opening a way to grow and develop (Prigogine and Stengers 1984; Morowitz 2002; Ho and Ulanowicz 2005). In ecosystems these development processes translate into an integrated spatial heterogeneity and biodiversity (Ulanowicz 1986; Ho 2013). As Ho (2013) suggests, these principles offer some basic criteria to understand what sustainability means for agroecosystems: a dynamic closure in nested space-time domains that enables a farm system to minimize entropy. Sustainable systems develop by interconnecting more life cycles within them so that the wastes from one cycle become resources for another (Figure.1.1).

Figure.1.1. How energy flow and storage characterizes the reproducing life-cyclesin any living systems andan integrated sustainable farm systemas well.



Source: taken from Ho(2013).

2.2. Unharvested biomass, reuses and integrated land-use management

Another key feature of agroecosystems is that some amount of biomass flows taken from the land is reused within the land system as an investment into the maintenance of its basic funds and services (Giampietro et al. 2013). This requires that a certain fraction of the Net Primary Production (NPP) within the study area remains unharvested or is returned to the agroecosystem (e.g. as manure), and also that a part of the land is set aside or kept sufficiently undisturbed to maintain biological diversity and the stability of biochemical cycles. The outcomeis a mosaic of land use and land cover types where human energy throughput is differentiated either in spatial intensity or temporal sequence. This was a distinct feature of preindustrial organic farm systems, where a diversity of cropping, grazing and woodland areas were interlinked by an integrated land-use management that created a variety of landscape mosaics (Margalef 2006).

We deem that these agricultural and forest mosaics were aimed to maintain a trade-off between exploitation and conservation, in a time when farming had to envisage how to achieve stability in the long run(Marull et al. 2008a; Marull et al. 2010; González de Molina and Toledo 2011). From this perspective, land use intensification appears as a process by which human labour supplemented by technical energy provided by industrial processes has reduced the requirement for less extensive land usages in the land matrix. When an integrated land-use management was no longer need, land cover diversity vanished. This could degrade the underlying ecosystem services (e.g. biodiversity) if some critical thresholds were surpassed, often with a long time lag. Energy analyses of agricultural systems usually neglect these indirect sustainability overheads (Giampietro et al. 1994; Giampietro 1997a).

Organic farmers bear extra burden of land—'land cost of sustainability'(Guzmán and González de Molina 2009; Guzmán et al. 2011)—compared to industrial ones as they take care of additional land per unit of output in order to maintain those environmental services provided by a well-integrated farm management. Given that this sustainability cost also appears in terms of human labour and energy expenditure, we emphasize the internal flows of biomass reused as one way to capture its role when accounting energy throughputs (see e.g. the biomass reusesthat led to barnyard services in Figure.2). Biomass reused to feed livestock is probably the most relevant example here: Apart from providing some components of final produce, such as meat, milk, eggs or wool, this often large energy flow is the basis for draught power and manure in organic farming systems (Krausmann 2004). Green manures, or weed covers in between the strips of wood crops, are other good examples. Another, more specific example, is charcoal, which can be used as fertiliser or soil conditioner, as well as fuel (Olarieta et al. 2011). All these internal loops use to contribute to the maintenance of a sound land-use integration linked with biodiversity, pest control, prevention of erosion and other services(Guzmán and Alonso 2008; Snapp and Pound 2008).Industrial farm systems tend to eliminate these loops by using external inputs as a substitute—even though they can only be partially substituted for some specific roles while this substitution entails a deep change in the whole patterns and processes of the agroecosystem.

Behind these ecosystem services lies an important emerging property of a well-integrated farm management, which (Marull et al. 2008a; Marull et al. 2010)labelled 'landscape efficiency'. Thanks to tight integration between diverse land uses, with different levels of energy throughputs per unit area, integrate farming can increase agroecosystem complexity which, in turn, allows to attain final produce greater than the invested energy in spite of all the sustainability overheads they bear (Giampietro et al. 1994; Giampietro 1997a; Naredo 2004a; Carpintero and Naredo 2006; Cussó et al. 2006a; González de Molina and Guzmán 2006; Krausmann 2006). This landscape efficiency gives way to many additional positive externalities provided by organic farmers, besides their direct produce.

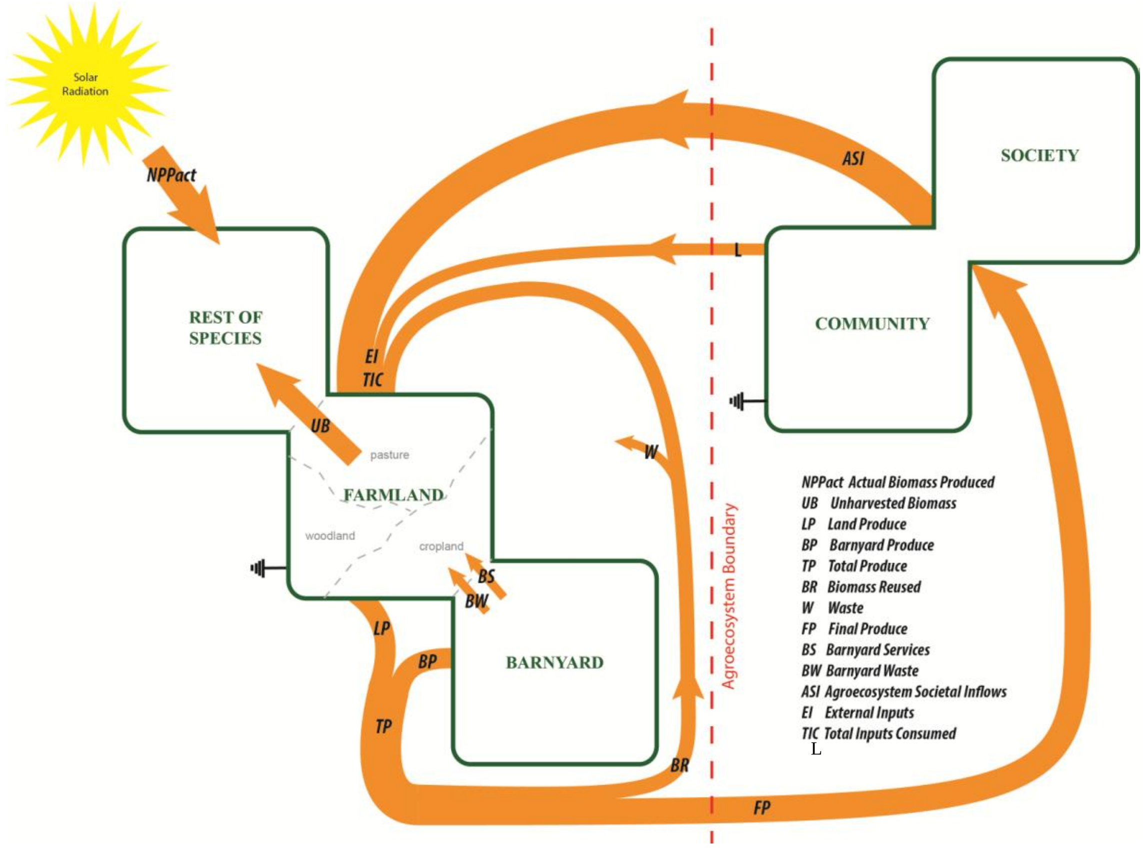
If energy balances are only accounted at the field or farm scale, energy efficiencies of industrialized farm systems may appear sometimes greater than of organic ones. In such cases the results can mask the positive externalities of the latter and the negative externalities of the former. This problem cannot be fully addressed through energy accounting alone, it requires a multi-criteria and integrated sustainability assessment. Nevertheless, we aim to bring some aspects related to this important issue to light by proposing an agroecosystem approach to energy accounting which takes these emerging properties into account. It uses a set of interrelated EROIs of agroecosystems aimed to capture the 'sustainability overheads' of an integrated land-use management.

2.3. Modelling energy funds and flows in agroecosystems

This approach draws on the Fund-Flow distinction put forward by (Georgescu-Roegen 1971). By funds we mean the permanent (and usually living) structures of the system that precede and remain after the time-span taken into account. They can provide a set of flows that link these funds one another, but always in a limited amount and only at a certain pace. Hence, sustainability means consuming an amount and composition of flows which does not undermine the system's funds—always remembering that only after placing the limits of a system we can identify the flows and distinguish them from the funds along the temporal process analysed. Unlike other sorts of non-renewable stocks, the renewable biophysical funds such as a fertile soil or a cattle herd cannot bring about a flow at any desired rate, or in a continuous manner, as they have to receive specific care and rest from time to time(Mayumi 1991).

Figure.1.2 presents a model of the key energy flows that draw the energy profile of an agroecosystem seen as a series of intertwined loops.The orange arrowsrepresent the flows of energy carriers from one converter to another, in a typical mixed farm system combining crop production with livestock husbandry. The green rectanglesrepresent the major funds,which act as converters linking one or several flows with others. For example, on Farmland (which could be cropland, pasture or woodland and scrubland and is measured in hectares) photosynthesis converts solar radiation into plant biomass. We also consider the Barnyardto be a fund, which represents the livestock and is measured in standardized Livestock Units of 500 kg. The animal digestion converts plant energy into animal biomass as well asinto barnyard services like draft power and manure. The Community of farm operators includes other energy converters, as the rest of Societydoes.

Figure 1.2. Basic model of energy flows on farms.



Note: The broken line represents the agroecosystem boundary; the orange lines the energy carriers; the green boxes are energy converters;the Net Primary Production in Farmland is the entry gate of energy from solar radiation within these boundaries; Final Produce are the energy carriers that exit them; External Inputs are the ones entering from the Community or Societal side.Source: Our own.

Notice that the size of these funds are not constant along time, e.g. in the example shown below woodland is bigger in 1999 than in 1860; but we consider that they do not change during the time scale of the process that we consider, i.e. one year.The definitions, accountancies and equivalences are summarized in Table1.1.

Table 1.1. Terminology, energy valuation and equivalences proposed in our bookkeeping of energy carriers of an agroecosystem.

Energy Carriers	Energy Form Accounted	Equivalences
Actual Net Primary Production (*NPP_{act}*)	Enthalpy	NPP= UB+LP
Unharvested Biomass (*UB*)	Enthalpy	UB = NPP–LP
Total Produce (*TP*)		TP = LP+BP
Land Produce (*LP*)	Enthalpy	LP = BR+FP-BP+FW
Barnyard Produce (BP)		
Final Produce (*FP*)		FP = CS+SP
Community Subsistence (*CS*)	Enthalpy	
Surplus Produce (*SP*)		
Biomass Reused (*BR*)	Enthalpy	
Farmland Waste (*FW*)	Enthalpy	TP = BR+FP+FW
Barnyard Services (*BS*)		BS = DP+M+BW
Draught Power (*DP*)	Work	
Manure (*M*)	Enthalpy	
Barnyard Waste (*BW*)	Enthalpy	
Labour (*L*)	Enthalpy of food intake by farmers multiplied by the ratio work time/total time adjusted by the energy requirement of different activities (plus the energy embodied in transport when food comes from outside)	
Societal Inflows (*SI*)	Embodied Energy &	SI = CSI+ASI
Community Societal Inflows (*CSI*)	Enthalpy	
Agroecosystem Societal Inflows (*ASI*)	(only Embodied Energy in food & feed bought outside)	
External Inputs (*EI*)		EI = SI+L
Total Inputs Consumed (*TIC*)		TIC = SI+L+BR

Source: Our own**.**

Both the Farmland and the Barnyard funds are internal to the agroecosystem, while all human functions either local or distant are considered external. Inputs to the system include human Labour (L), Community Societal Inflows (CSI) and Agroecosystem Societal Inflows (ASI), which together make up External Inputs (EI). Outputs include the Final Produce (FP) of cropland, woodland, and livestock herds for human use, including subsistence consumption by the local Community and any Surplus Produce (SP) sold or transferred by other means to the rest of Society. Importantly, Biomass Reused (BR) cycles within the system and is accounted as an input to farmland included in the Total Inputs Consumed (TIC). Another important distinction arises between Land Produce seen as the harvested share of the Net Primary Production (NPP), and the unharvested (UB) biomass left available for all other species.

Another important issue here is establishing a clear-cut distinction between reuses (BR) and wastes (W), particularly when in industrialized farm systems they cannot be considered as a proper reuse as defined in section 2.2 because they do not contribute to the complexity of the agroecosystem as explained in section 2.1. We represent two W flows in the 1999 flowchart (Figure.1.5), one parallel to BR (FW) and the other as an exit from the Barnyard (BW). Examples for such waste flows are burnt or disposed crop residues and the excess of dung slurry from intensive livestock breeding in feedlots. If this dung slurry is e.g. spread over cropland where chemical fertilisers are also applied, the ensuing over-fertilisation cannot be absorbed by the crops grown thereand most of its nitrogen compounds end up as water pollutants or greenhouse gas emissions. Notice that in our case study the energy content of this Barnyard Waste was equivalent to 92% of the Final Produce in 1999.

All of these flows are accounted using the Gross Calorific Value (GCV) of their Enthalpy when we are dealing with energy carriers obtained from within the agroecosystem under analysis (they are detailed in Annex 1.B). When they come from outside, we account these Societal Inflows adding also the Embodied Energy, i.e. the energy required to produce and supply them to the system boundaries(Brown and Herendeen 1996).

2.4. Accounting for labour by adopting a farm-operator standpoint

How to include human labour in energy analysis of agricultural systems is a much debated topic (Fluck 1981; Odum 1984; Jones 1989; Giampietro and Pimentel 1990; Fluck 1992; Brown and Herendeen 1996; Murphy et al. 2011; Giampietro et al. 2013). According to the agroecosystem approach shown in Figure 1.2 we consider human labour as an external input, which is accounted for as the fraction of the average diet of farm-operators that corresponds to the work time performed in the agroecosystem—taking physiologically different energy requirements of human activities into account. The components of their food basket are energy assessed following the same rule outlined above: we use gross calorific values (GCV) of food produced in the observed farm system, whereas in supplies coming from outside we add the energy spent to process and deliver the food products to the population considered (embodies energy).[2]

We base this labour accounting on what Fluck(1992)has termed the total energy of food metabolized while working. The rationale behind the time-budget adjustment to the work actually done, out of total time, is to recognize that farmers or agricultural labourers eat food to perform many other aims in life besides work.[3] In this way our analysis remains open to the choices made by these farm-operators when allocating their own time.

Another perspective on human labour would be to assesshow many non-farming people could be provided with food, fuel and fibre by these farm-operators. In this case we would have to take the time allocation made by the local community as given and to consider not only the whole food basket consumedby the agriculturally active population whatever their time allocation, but also the consumption of the dependent non-working population as well—that is, considering that the entire local community has to reproduce itself throughout time(Norum 1983; Giampietro and Pimentel 1990; Fluck 1992; Brown and Herendeen 1996; Odum 2007; Giampietro et al. 2013).

Both perspectives are necessary, either the one performed from a farm-operator vantage point in the agroecosystem or the other performed from a wider societal standpoint. They cannot be adopted at the same time, but can be combined in a multidimensional and multi-scalar assessment—other authors have done so for instance using the MuSIASEM methods (Giampietro et al. 2013; Scheidel et al. 2013). Here we only apply the former approach to human labour accountancy that corresponds with the system boundaries adopted.

3. A single EROI is not enough

How can an EROI be calculated of such a cyclic, rather than a linear system? The most conventional EROI used inagricultural systems is the one that we call external final EROI (see section3.1). However a cyclical approach has to go beyond a linear input-output perspective that identifies energy efficiency with a

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[2]In this very special case, however, we do not extend the embodied accountancy up to the energy spent in producing the food coming from outside—because then we would be double counting the food grown in one agroecosystem that is going to be consumed by people working in another.

[3] In contrast to peasant labour, slave labour would be regarded as an internal flow of the agroecosystem. Slaves were sustained by landowners only as a means of production and were treated similarly to draught animals, or *instrumentumvocale*likeancient Romans said.

single EROI ratio between the output of consumable agricultural products and the industrial or technical inputs that supplement human labour. Since such a linear perspective falls short of capturing the significance of the unharvested biomass, as well as of that part of harvested biomass reused within the agroecosystem (like seeds, green manures or the feed converted into draught power and animal manure), we propose a set of four different EROI indicators to adequately capture the cyclical character of energy flows in agroecosystems.

The definition of these four EROIs is based on the inclusion and exclusion of the flows of Biomass Reused or External Inputs in the denominator, and by using Final Produce or Net Primary Production actually photosynthesizedin the numerator. The flow of Barnyard Services,such as draft power and manure, is omitted from all final calculations in order to avoid double counting (however, it is shown as grey arrow fromFigure 1.3 onwards).In the following sections we present this set of interrelated EROIs by using as examples two energy balances of the farm systems existing circa 1860 and in 1999 in five Catalan villages of the Vallès County (North East of Iberia). The farming systems in thisarea have been investigated in a series of interdisciplinary case studies (Cussó et al. 2006b; Marull et al. 2008a; Tello et al. 2008a; Garrabou et al. 2010; Olarieta et al. 2011; Tello et al. 2012). The broad database created has been thoroughly recalculated and calculations and methodological specifications can be found in Marco et al. (forthcoming). The list of EROIs appears in Table 1.2.

Table1.2. List of EROIs obtainedin the five Catalan villages of the Vallès County c.1860 and in 1999.

	c.1860	1999
Final EROI (FEROI = FP/TIC)	1.05	0.21
External Final EROI (EFEROI = FP/EI)	10.49	0.23
Internal Final EROI (IFEROI = FP/(BR+W))	1.17	2.18
NPP EROI (NPP /TIC)	3.18	0.41
NPPEROI -Final EROI	2.12	0.20

Source: our own, recalculated from Cussó, Ramón Garrabou, et al. (2006).

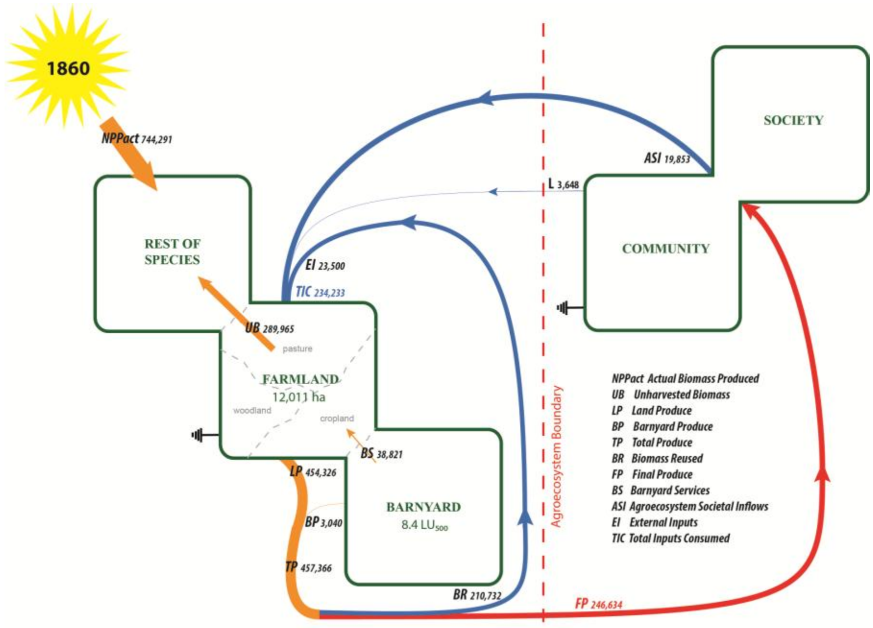
3.1. The dependence on Societal Inflows: External Final EROI

External Final EROI relates external inputs to the final output crossing the agroecosystem boundaries (Carpintero and Naredo 2006; Pracha and Volk 2011). This ratio links the agrarian sector with the rest of the energy system of a society—and thus assesses to what extent the agroecosytem analysed becomes a net provider or rather a net consumer of energy. It is also very relevant when considering the so-called 'Podolinsky principle' put forward by Martinez-Alier & Naredo (1982), according to which the human labour performed in agroecosystems provides a surplus of available energy for the rest of human society in the form of solar energy converted into biomass.[4] However, as explained above, a more precise assessment of this societal link would require adjusting the human labour accountancy adopting a reproductive approach, which means adding up the energy requirement of a Total Time Budget Analysis including non-farm activities and all members of the local community. Being accounted this way, External Final EROI also becomes very important for evaluating the agricultural component of the 'Law of minimum EROI' (Hall et al. 2009; Hall and Klitgaard 2012)—which states that for any social system to survive and grow it must attain a minimum EROI able to support continued economic activity and social functions.

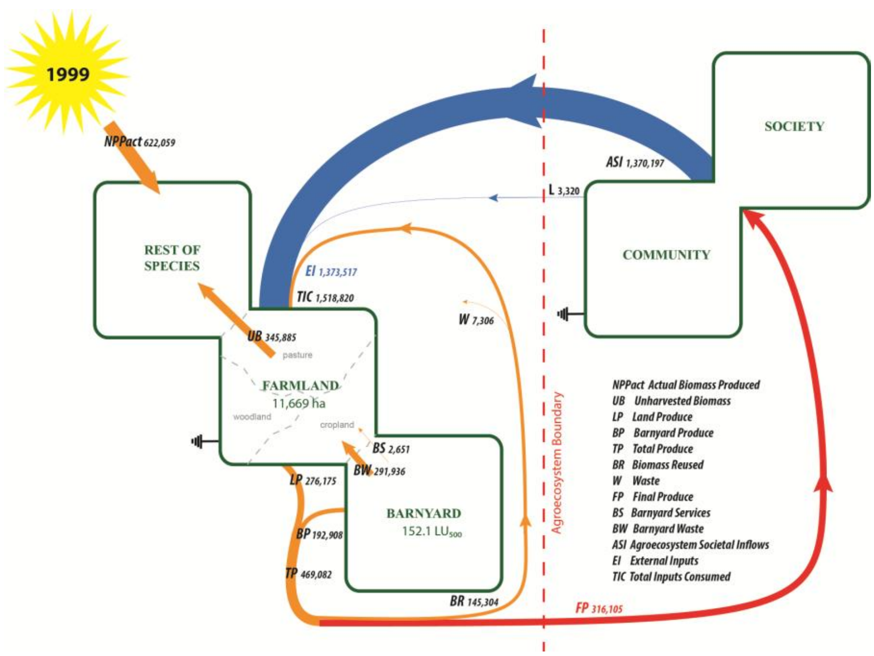
Anyhow, as long as we focus our energy analysis on the farm-operators standpoint we kept accounting human labour by the energy requirement only during farm working time. Recall that, according to the system boundaries adopted, human labour and domestic residues was usually the most relevant External Input in past organic agricultural systems. Consequently these always obtain higher External Final EROIs compared with current conventional ones, e.g. in the Catalan example it dropped from 10.49 circa 1860 to 0.23 in 1999 (Figure1.3).

[4]We are not interested in discussing here the Podolinsky principle from a history of economic thought standpoint. It cannot be any doubt that this principle is very relevant either if (Burkett and Foster 2008) are right or not in pointing out the limitations of the original Podolinsky's proposalsin 1880 (Podolinsky 2004), or when they suggest that Martinez-Alier & Naredo (1982) went too far when assigned to him the original idea of assessing if the energy relationship between agriculture and the rest of society involves an overall net producing or a net consuming character.

Figure 1.3. External Final EROI of the Catalan case study c.1860 and in 1999.



$$\text{External Final EROI} = \frac{\textit{Final Produce}}{\textit{External Inputs}} = \frac{FP}{EI}$$



External Final $\text{EROI}_{1860} = \frac{246{,}634\,\text{GJ}}{23{,}500\,\text{GJ}} = 10.49$ External Final $\text{EROI}_{1999} = \frac{316{,}105\,\text{GJ}}{1{,}373{,}517\,\text{GJ}} = 0.23$

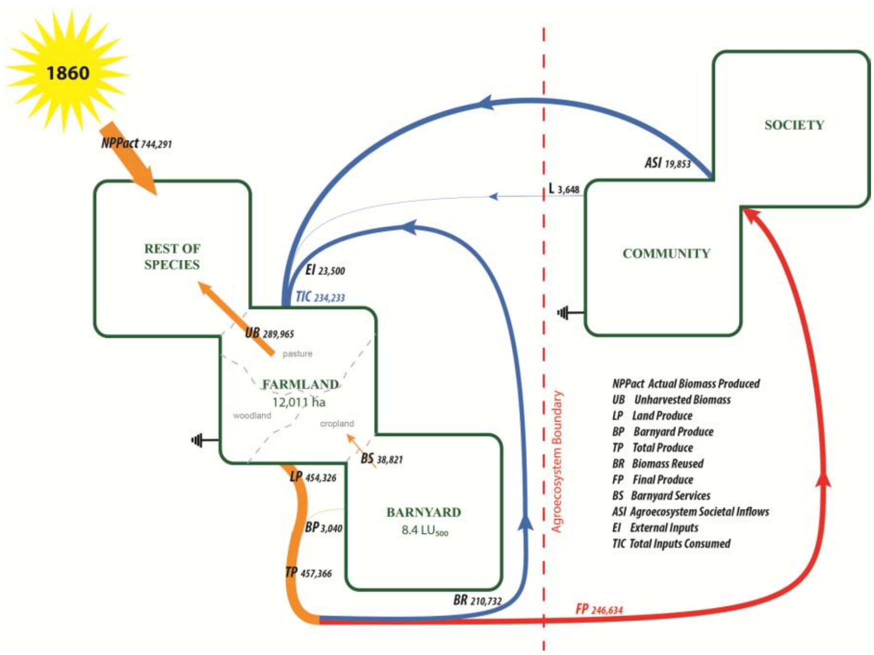
Source: our own.

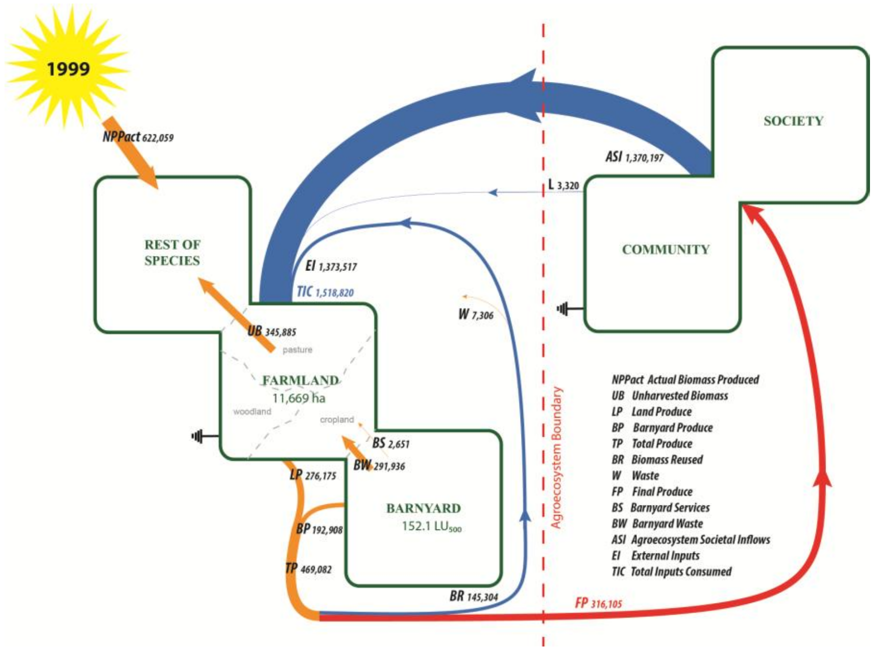
3.2. Meeting human needs: the Final EROI

Final Produce (FP) is a net supply of energy carriers able to be consumed by the local population or for use in other socio-economic systems. This does not mean that the rest of intermediate inputs and by-products included in Land Produce but excluded in FP are of no use. On the contrary, we have to distinguish the actual energy losses occurringin conversions from that part reused as intermediate inputs through internal loops of the agroecosystem, which can be defined as energy and materials needed for the renewal of its funds and processes (Giampietro 1997a; Giampietro and Mayumi 1997). Adding Biomass Reused (BR) to External Inputs (EI) we get Total Inputs Consumed (TIC). That is, Final EROI assesses how much external and internal input must be invested by a farm operator to get a given basket of human consumable biomass products.In the Catalan example it dropped from 1.05 circa 1860 to 0.21 in 1999 (Figure 1.4).

Figure 1.4. Final EROIs of the Catalan case study c.1860 and in 1999.

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





Final $EROI_{1860} = \frac{246{,}634\,GJ}{234{,}233\,GJ} = 1.05$ $FinalEROI_{1999} = \frac{316{,}105\,GJ}{1{,}518{,}820\,GJ} = 0.21$

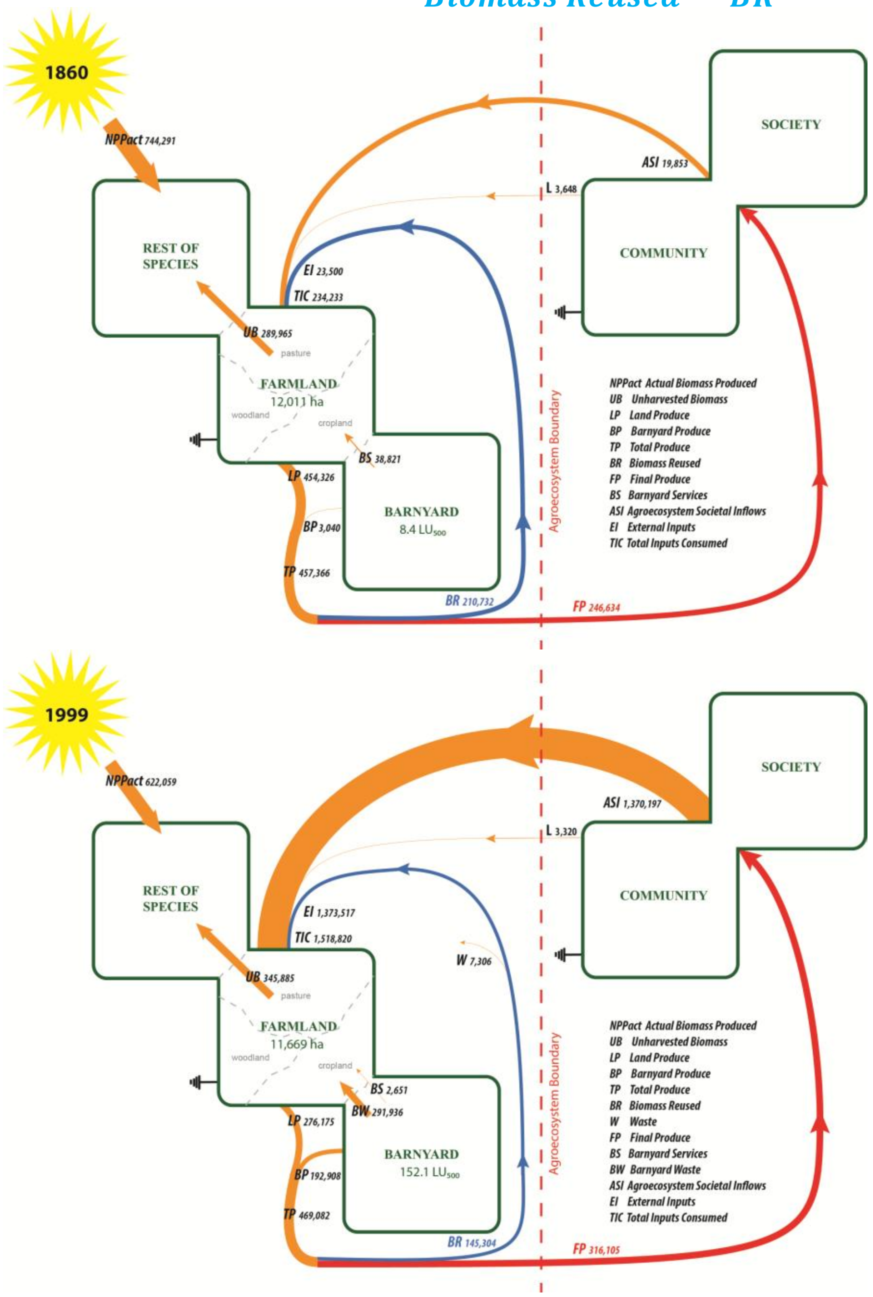
Source: our own.

3.3. *Reusing to keep up agroecologicalfunctioning: Internal Final EROI*

Internal Final EROI assesses the portion of Land Produce reinvested in the agroecosystem as Biomass Reused in order to get a unit of consumable Final Produce. The relative amount of these internal flows exposes a clear-cut distinction between historic solar-based agricultural systems compared with fossil fuelled industrial ones at present, as organic farm systems nearly always bear greater internal flows per unit of output. For example, in our Catalan example Internal Final EROI increased from 1.17 c.1860 to 2.18 in 1999 (Figure 1.5). In this specific case, the directionality of change must be carefully understood given that it can mask a greater investment in keeping up the ecological performance of the agroecosystem's funds—and hence, the fact of bearing a higher sustainability cost.

Figure 1.5. Internal Final EROI of the Catalan case study circa 1860 and in 1999.

$$\text{Internal Final EROI} = \frac{\textit{Final Produce}}{\textit{Biomass Reused}} = \frac{FP}{BR}$$



Internal Final $EROI_{1860} = \frac{246{,}634\,GJ}{210{,}732\,GJ} = 1.17$ Internal Final $EROI_{1999} = \frac{316{,}105\,GJ}{145{,}304\,GJ} = 2.18$

Source: our own.

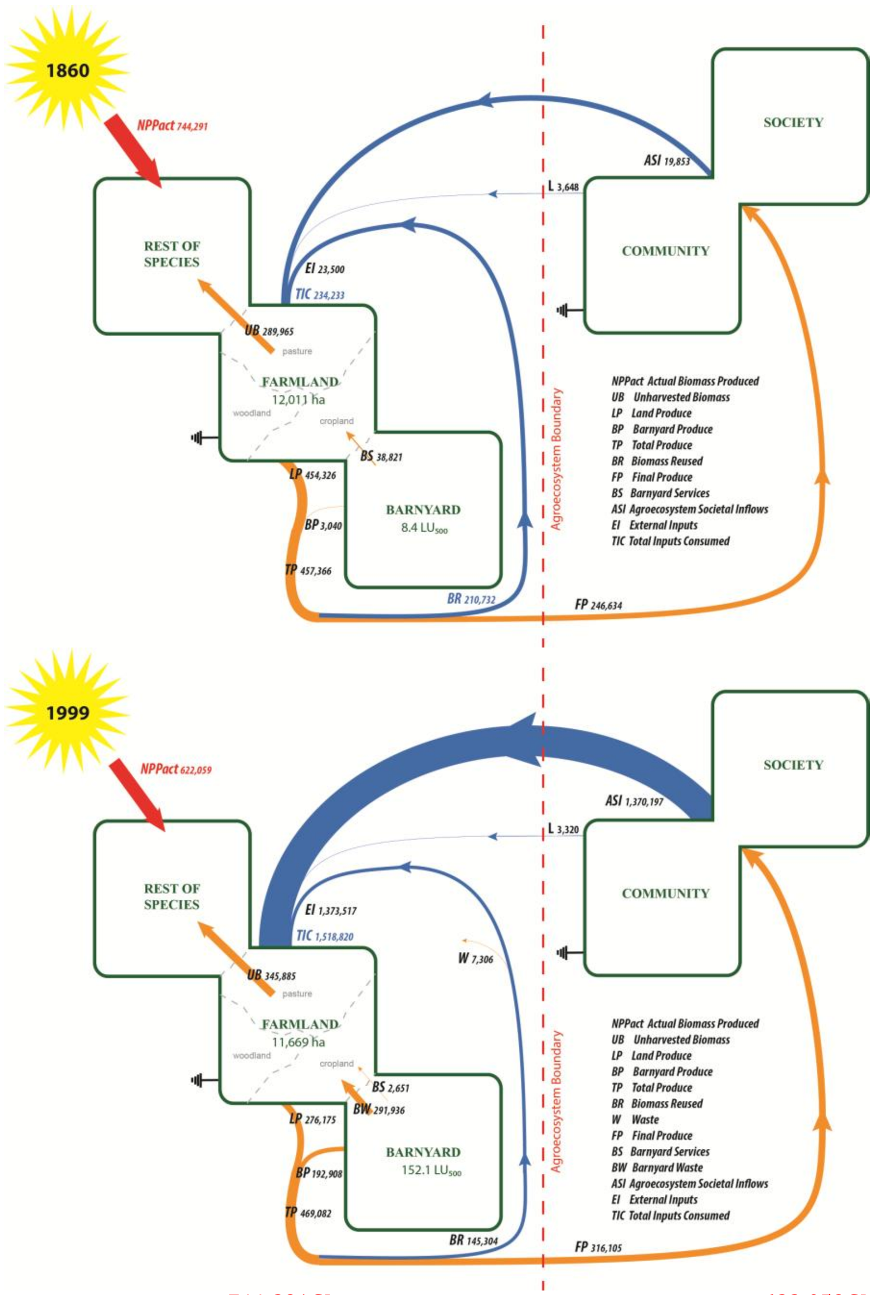
We deem that reusing a relevant share of Land Produce can be related to a highdiversity of land covers, ecotonesand habitats in agro-forest landscapes, as Marull et al., (2010, 2008a)pointed out for this same Catalan case and periods, or as been stated by Gustavsson et al. (2007) for Swedish pastures. This would be true as long as BR constitutes a smooth and repeated intermediate disturbance (as opposite to climax community) that helps to maintain ecological functionality,as suggested by Margalef (2006),and enhances resilience. See Annex 1.A for an explanation of BR. However, this working hypothesis on the significance of BR and the related EROI indicators requires further research and in particular combining EROI analysis with landscape ecology methods. As an additional tool to support this type of research we propose a further EROI indicator in the next section, which takes the NPP left in agroecosystems for food chains into account.

3.4. NPPEROI

NPPEROI expresses the energy return in terms of the whole biomass photosynthesized in agroecosystems which is available to sustain humans as well as the rest of heterotrophic species. These other species, as well as the ecosystem services they provide, continue functioning conditioned by the flow of energy and information that farmers invest. Hence, the total biomass annually produced by the agroecosystem(NPP) can also be seen from a farm-operator standpoint as a result of their investment(Figure 1.6).

Figure 1.6. Net Primary Production EROI of the Catalan case study c.1860 and in 1999.

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



$NPP_{act}\ EROI_{1860} = \frac{744{,}291\,GJ}{234{,}233\,GJ} = 3.18$ Internal Final $EROI_{1999} = \frac{622{,}059\,GJ}{1{,}518{,}820\,GJ} = 0.41$

Source: our own.

In former sections we showed the recalculated energy flows for the farm systems described in Cussó, Garrabou, Olarieta, et al.,(2006a).To these we added new data requiredto estimate the Unharvested Biomass (UB)c.1860 and in 1999. In cropland we considered the share of the crop NPP consumed during the growing season by other species (Oerke et al. 1999), and the weeds associated to different crops(Bradley et al. 2010; Guzmán et al. 2014; Sheaffer et al. 2014).For other land uses we calculate the NPPminus the biomass extracted by humans that year (NPP_h) to assess the unharvestedNPP,using the data provided byGovierno de Navarra(2012) andOlea(2010)forgrassland,byCañellas (1991)for scrublands,and byGracia et al. (2000-2004) for forests. The results are summarized in Table 1.3.

Table 1.3. Values of total (NPP) and harvested (NPPh) Net Primary Production estimated in the Catalan study area c.1860 and 1999.

Main land uses and land covers	c.1860					1999				
	NPP_h			NPP_{act}		NPP_h			NPP_{act}	
	ha	*MJ/ha*	*GJ*	*MJ/ha*	*GJ*	ha	*MJ/ha*	*GJ*	*MJ/ha*	*GJ*
Cropland	3,235	80,572	260,647	120.208	388,865	2,511	104,177	261,558	122,5	307,563
Pastureland	2,555	9,62	24,577	25.200	64,381	232	4,29	993	25,2	5,834
Woodland	3,624	46,657	169,103	80.302	291,046	3,807	3,456	13,158	80,302	305,709
Scrubland	n.a.	n.a.	n.a.	n.a.	n.a.	110	--	--	26,851	2,954
Total land uses	9,414	--	454,326	--	744,291	6,659	--	275,709	--	622,059

Note: NPPh: Net Primary Production harvested (that equals Land Produce). NPPact: annual Net Primary Production in the actual land covers in the study area.Source: our own, calculated as explained in the text.

3.5. Relating Final EROI with its internal and external returns

The Catalan examplesof c.1860 and 1999 show two rather opposite energy profiles (Table 1.2).One of the main characteristics of the latter is that, apparently, Final EROI does not need to be high in order to meet human needs. This is so because there has been a historical substitution trend from internal (BR) towards external inputs (EI) throughout the socio-ecological transition from historic organic agroecosystems to industrialized farm systems. To what extent the change in final EROI has been due to increased EI, or abandonment of BR? This leads us to interrelate Final EROI with its respective internal(IFEROI) and external (EFEROI) returns.By substitution[5], it is easy to reach the following Eq. (1.1)

[5]Let us call a the FP, b the EI, c the BR, p the Final EROI, q the External Final EROI and r the Internal Final EROI. Then $q = \frac{a}{b}$, which is the same as $b = \frac{a}{q}$; and $r = \frac{a}{c}$, which is the same as

which tells us that Final EROI equals the product between its internal and external returns divided by their sum:

$$Final\ EROI = \frac{EFEROI \cdot IFEROI}{EFEROI + IFEROI} \text{Eq. (1.1)}$$

Eq.(1.1) incurs in decreasing returns at any point: to get any increase in the Final EROI proportionally greater increases in either internal or external returns or both are needed. However, it is possible to address a declining Final EROI by substituting to some extent Biomass Reused (BR) for External Inputs (EI). Reduction in EI would increase the external return (EFEROI), which in turn would compensate the decreasing internal return (IFEROI) to obtain a given Final EROI. The opposite is true. A declining Final EROI could be addressed by substituting EI for BR to some extent. This reduction in BR would increase the internal return (IFEROI), which in turn would compensate the decreasing external return (EFEROI) to obtain a given Final EROI.[6] As will be explained in next chapter, Eq. (1.1) can be used to perform a decomposition analysis that will assessthe relative impact of the changes experienced by either external or internal returns in any historical shift experienced from one Final EROI to another, or to find out the optimal improvement pathways of energy throughputs existing in any agroecosystem at any moment in time.

The results obtained by applying this decomposition analysis to the Catalan case study in 1860 and 1999 led to some interesting conclusions. The sharp decrease in final EROI experienced by the latter industrialized farm system was mainly due, as expected (Schroll 1994; Dalgaard et al. 2001), to the increase in external energy inputs used in tractors, machinery, chemical fertilisers, pesticides and feeder cattle imports for feedlotswhich together contributed 116% of the total decrease in Final EROI from 1860 to 1999— notice that the huge amount of EI was 2.2 higher than the actual NPP in the study area (Figure 1.6). However, it was also due to getting rid of reuses and the abandonment of an integrated land-use management that counteracted up to 16% the decrease in the joint energy

$c = \frac{a}{r}$. Given that $p = \frac{a}{b+c}$, we have $= \frac{a}{\frac{a}{q}+\frac{a}{r}}$, and $p = \frac{a}{\frac{ar+aq}{qr}}$, which leads to $p = \frac{a}{\frac{a(r+q)}{qr}}$, and finally to $p = \frac{qr}{r+q}$.

[6]As explained in section 2.2., these substitutions between BR and EI are only possible in practice for some specific functions but not others. They usually entail deep changes in agroecosystem functioning.

return.Had such a counterbalancing effect not taken place, the drop in Final EROI would have been even higher.

3.6. Relating Final and NPP EROIs: the role of unharvested biomass

Recall that Final EROI expresses the return on energy invested in terms of the final product consumable by humans. Like the obverse of a coin NPP EROI expresses the return in terms of energy available to sustain humans as well as the rest of heterotrophic species. From this perspective we are assuming that the energy invested (TIC) in an agroecosystem by the farm-operators to get a Final Produce (FP) is not lineal or single-purpose. They create indeed a set of loops from a specific flow of NPPwhose beneficiaries are not only them but other species as well.

We defined above (sections 2.2 and 2.3) the flows that we understand as resources left for other species, which are Unharvested Biomass (UB) and Biomass Reused (BR). According to Table 1.1:

$$NPP = UB + LP = UB + BR + FP - BP \qquad \text{Eq. (1.2)}$$

Using the above identity we arrive at Eq. (1.3) that relates NPPEROI with Final EROI[7]:

$$NPPEROI - Final\ EROI = \frac{UB+BR}{TIC} - \frac{BP}{TIC} \text{Eq.(1.3)}$$

If Eq. (1.3) is seen like a zero sum game we arrive at an interesting hypothesis: the greater the difference between NPPEROI and Final EROI, the higher the capacity of an agroecosystem to shelter other species is. Conversely, the increasing dependence on external inputs goes hand in hand with biodiversity loss—as has been tested by many observers(Matson 1997). No doubt, this assumption has to be checked with wider evidence than the one offered here, and needs to combine energy analysis with landscape ecology assessment. For the time being we suggest to interpret Eq. (1.3), as well as the results shown in Table 1.3 and Figure.1.5 to 6, considering that for an agroecosystem to host a great deal of species there must be a balance between unharvested biomass and habitats of low human colonization or none[8]. Hence biodiversity would require having the two things at the same time

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[7] The second term in the right side of this identity is only an accountancy adjustment needed to avoid double counting Barnyard Produce (BP), which belongs to Final Produce (FP) but not to Land Produce (LP). Hence, the meaning of Eq. (3) lies in the first term on the right side that relates UB and BR with TIC.

[8] Calculating the set of EROIs here proposed help to reveal how misleading it is to consider many less undisturbed agricultural lands as 'underused' or 'unused'—as it is currently alleged by the

in the same area: habitats and food chains free for a wide range of species. Habitats may remain empty if there is not enough biomass free of human appropriation (UB). But a lot of unharvested biomass with a low diversity of habitats would lead at its turn to big populations of a limited number of species. This reasoning can be applied to our set of EROIs as long as we assume that the relevance of BR has a lot to do with land cover diversity and the availability of habitats in the land matrix—a working hypothesis which we intend to demonstrate by developing this approach in further research.

4. Discussion of results

If we are right in the above assumptions, more research on the contribution of BR and UB to biodiversity in agroecosystems is needed.As explained in section 3.3, the lowering of BR in industrial farm systems went hand in hand with a homogenization of cropland and a simplification of the landscape matrix. The simultaneous decrease observed during the second half of the 20th century in agroforest mosaics, as well as in many biodiversity indicators, can be seen from this perspective as a kind of big natural experiment for this line of research (Tscharntke et al. 2005; Bianchi et al. 2006; Gustavsson et al. 2007; Marull et al. 2008b; Fischer et al. 2008b; Marull et al. 2010; Tello et al. 2014).

Trying to replace biomass reused with external inputs characterizes the socio-ecological transition from traditional organic agricultures to industrialized farm systems reliant on fossil fuels.Conversely, organic farmingtends to save external inputs by replacing them with internal biomass reused through a strategy called Low External Input Technology (LEIT; see Tripp, 2008).Currently, the scientific and political interest in land sparing (that is, setting aside of land for biodiversity conservation) combined with wildlife-friendly farmingis growing worldwide (see a review in (Fischer et al. 2008a). We think thatif ourbasic hypothesis is true, the link betweenNPPEROI and Final EROI would provide a useful indicator to assess in energy termsthe capacity of an agroecosystem to host biodiversity.

According to Table 1.3, the NPPin the existing land covers would had been 20% higher circa 1860 than in 1999—partly due to the loss of farmland given over to built-up land, but also because of the decrease in weeds and other adventitious plants. At the same time the NPP_h decreased, in proportion of NPP,from 61% to 44%, mainly due to land abandonment and reforestation. As a result, the total

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promoters of land-grabbing disregarding the agroecological role they play for many rural communities (Scheidel et al. 2013) amount of unharvested biomass became 19% higher in the latter than in the former date. Nevertheless, our NPPEROI was nearly eight times higher in 1860 than in 1999 (Table 1.2)meaning that the available energy flows for other species per unit of farm-operators investment (TIC) was clearly wider in the organic agroecosystemof 1860 than in the industrial farm system of 1999. This is confirmed when Final EROI is subtracted to NPPEROI: the result c.1860 was more than ten times higher than in 1999 (Table 1.2).

These examples help to explain why the path followed by industrialized agricultures eliminating internal reuses, and relying on increasing external fossil inputs, lead to a loss of habitats. At the same time the amount of unharvested biomass increased in absolute terms as a result of the higher Final Produce per unit of cropland made possible by direct and indirect inputs of external energy, above all from fossil fuels, which in turn allowed limiting cultivation in the best land and setting aside many others.However, this has given way to a very unbalanced relationship between habitats and biomass left free from human appropriation by industrial farm systems at present. A usual outcome has been the typical population imbalances that make certain species to become plagues because of the lack of regulation that biodiversity provides(Bianchi et al. 2006; Tello et al. 2014).

The opposite LEIT strategy of organic farming also requires a balance between the human appropriation of NPP and the keeping of biodiversity. By reinvesting as reuses a substantial portion of the Land Produce, and keeping an integrated land-use management, farmers seek to balance human disturbance with the increasing complexity and resilience of agroecosystems. They will also face an upper limit though, given that any increase in harvested biomass (NPP_h), either reused or consumed by humans, decreases the unharvested biomass (UB) available to other species. From a certain point, land-use intensification will cease to be sustainable even in an organic agriculture (Erb 2012; Krausmann et al. 2012).Knowing where these critical thresholds in energy throughputs are placed in different agroecosystemswould be very useful for designing more sustainable farm systems in the future. Ourenergy assessment has to be understood as a starting point for a deeper analysis of biodiversity endowment in agroecosystems that is to be developed by taking into account the complexity dimension of organized information.

5. Concluding remarks

Ourapproach to characterize and assessthe energy profiles of agroecosystems,aimed at comparing them inpast orpresent times and to foresee other more sustainable in future, can be summarized in three main points. First of all, a single EROI is not enough since a relevant share of energy flows driven by the farm-operators cycles again into the agroecosystem as a loop. Therefore we propose calculating four interrelated EROIs, each of which captures different sides of the agroecosystem functioning: Final EROI, External Final EROI, Internal Final EROI and NPP EROI.Secondly, wehypothesize that taken together they can bring into light the missing link between energy performance and biodiversity.

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

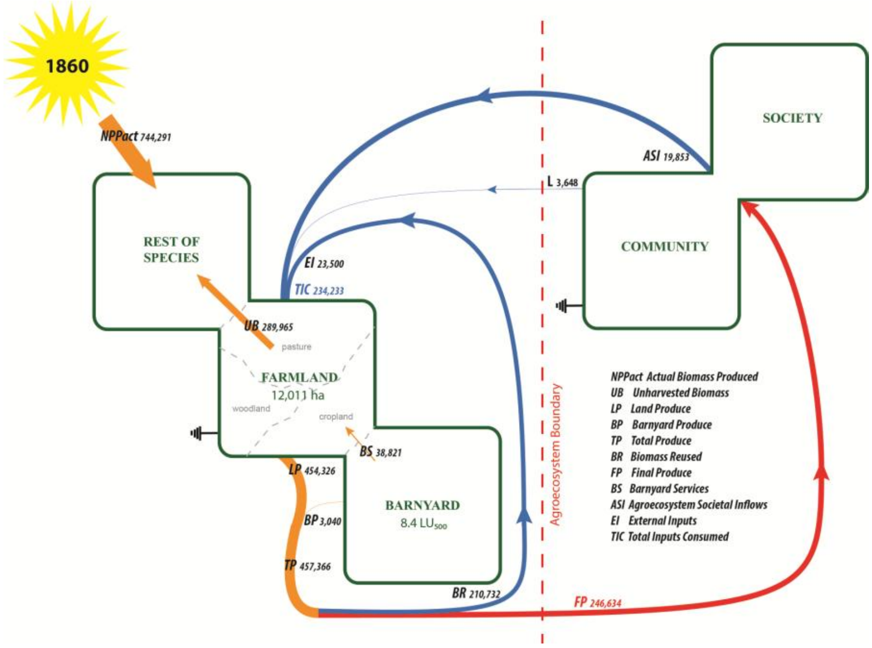
Chapter 2. Opening the black box of energy throughputs in agroecosystems: a decomposition analysis of final EROI into its internal and external returns (the Vallès County, Catalonia, c.1860 and 1999)[1]

1. Introduction

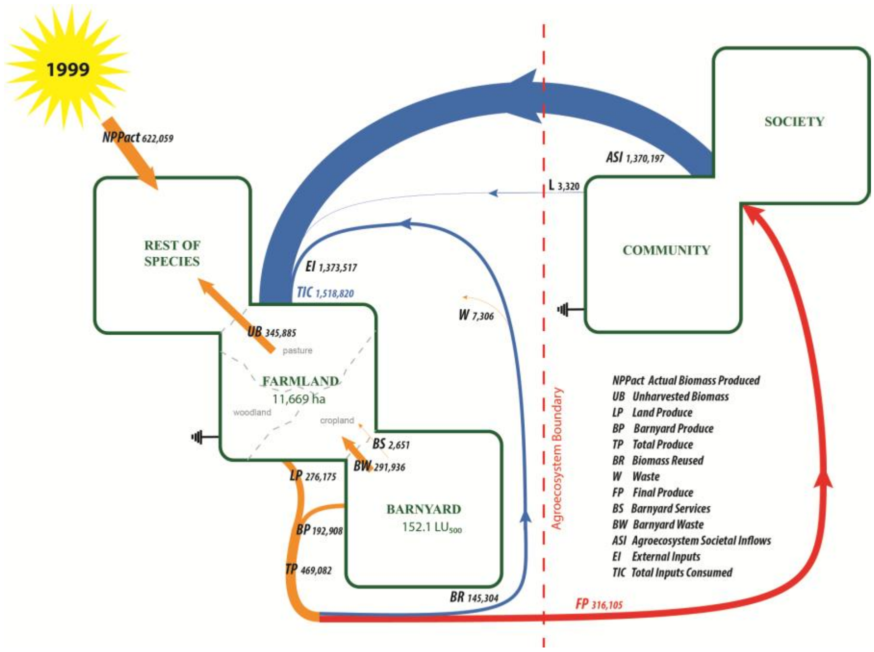
Agroecosystems, as hybrid human-natural systems, require a special treatment when assessing energy returns on investment (EROI) (Giampietro et al. 2011; Hall 2011; Pelletier et al. 2011; Hall and Klitgaard 2012; Giampietro et al. 2013). A linear approach in which farm operators invest energy carriers and, after a conversion process, obtain an energy output cannot give a proper account of their complexity (Leach 1976; Odum 1984; GiamPietro and Pimentel 1991; Giampietro et al. 1992b; Giampietro et al. 1992a; Giampietro et al. 1994; Giampietro 1997a; Odum 2007; González de Molina and Toledo 2011; Giampietro et al. 2013). Seen as nature transformed by human activity, the energy profile of a farm system has to be drawn as a series of intertwined loops—like in Figure 2.1, a simplified outline of the main energy flows in a Catalan case study c.1860 and in 1999 (see also Figure. 2.6 and Annex 1.B).

[1] This paper was coauthored by E. Tello, V. Sacristán, G. Cunfer, G.I. Guzmán, M. González de Molina, F. Krausmann, S. Gingrich, R. Padró, I. Marco, D. Moreno-Delgado. My contributions were rebuilding all the calculations of the case studies together with I. Marco and R. Padró, participating actively in the construction of the model and searching and discussing references.

Figure 2.1.Energy profiles of farm systems in five municipalities of the Vallès County (Caldes de Montbui, Castellar del Vallès, Palau-solità i Plegamans, Polinyà and Sentmenat) in Catalonia, Spain, c.1860 and in 1999.



$$\text{Final EROI}_{1860}=\frac{246{,}634\,\text{GJ}}{234{,}233\,\text{GJ}}=1.05$$



$$\text{Final EROI}_{1999} = \frac{316{,}105\,\text{GJ}}{1{,}518{,}820\,\text{GJ}} = 0.21$$

Source: our own.

The primary data of these five Catalan villages has been taken from previous publications (Cussó et al. 2006a; Tello et al. 2006; Cussó et al. 2006b; Garrabou et al. 2010) and has been improved using additional historical sources and updated energy converters, and adapting all accountancies to the bookkeeping method we propose in a series of recent articles (Galán et al.; Marco et al.). This paper focuses on a specific aspect of this novel approach to agricultural EROI's, namely the contrasting energy profiles of organic versus industrial farm systems regarding their mainly cycling or linear character, and aims to contribute to the methodological advance of this field of study.

Agroecosystems arise when a community of farm operators invests a certain amount of energy carriers (like human labour, animal or mechanical work, seeds, fertilisers and so on) to create a new cultural landscape from terrestrial ecosystems. As human-colonized ecosystems they retain their own ecological processes but cannot maintain and replicate themselves over time without a repeated investment of energy and information, in addition to naturally occurring solar radiation and photosynthesis (Altieri 1989; Gliessman 1998; Altieri and Nicholls 2005; Snapp and Pound 2008). Their continuous functioning also requires regulatory services mainly performed by ecological processes on less-disturbed land (Odum 1984; Giampietro et al. 1992b; Giampietro et al. 1992a; González de Molina and Guzmán 2006; Guzmán and González de Molina 2009; Guzmán et al. 2011).

Thus, besides economic yields any sustainable farm system has to maintain its agroecological complexity—sometimes labelled 'natural capital', although we prefer using Georgescu-Roegen's term of 'funds' meaning that unlike other sorts of stocks they have to rest and receive specific care from time to time, and cannot bring about a flow at any desired rate or in a continuous manner (Georgescu-Roegen 1971; Mayumi 1991). In past organic agroecosystems this ecological constraint was met by integrating different land units where various levels of energy throughput per unit area were applied. These mixed agro-forestry-grazing systems historically evolved into a variety of agricultural landscape mosaics, adapted to specific bioregions and societal needs, aimed to maintain a trade-off between exploitation and conservation (Margalef 2006; Marull et al. 2010).

Difficulty in maintaining these integrated landscape mosaics has arisen when external socioeconomic flows become substitutes for reinvestment of internal flows of organic matter to increase yields per unit of cropland or labour. While greater reuse flows seem to be related with a larger complexity of agroecosystems, substituting external energy inflows for internal reuse of biomass may entail a linear simplification as can be observed in many industrial farm systems. Therefore, any sustainable assessment of agroecosystem's performance has to open the black box of energy throughputs in order to highlight the key role played by internal flows of biomass reused.

In this article we aim to shed some light on this important issue by proposing a decomposition approach of Energy Returns On Inputs (EROIs) of agroecosystems, which explicitly differs between internal or external components, and by comparing the energy yields at their entrance or exit boundaries (i.e. photosynthetic net primary production or final produce). Section 2 summarizes the energy profiles of agroecosystems using four interlinked EROIs. Section 3 presents the equation relating Final EROI with Internal Final EROI and External Final EROI, and explores the properties of the conic surface that allows plotting their relationships in different agroecosystems. Section 4 uses the same equation and graphs to find out the optimal improvement pathways of Final EROI by varying internal or external returns. Section 5 develops a mathematical decomposition to assess the impact of internal reuses or external inputs in the shift experienced by Final EROI from one date to another. Section 6 concludes discussing the empirical results, and presents the working hypothesis that organic and industrial farm systems may tend to cluster into two main typologies.

2. Modelling energy funds and flows in agroecosystems

The starting point of our approach is to emphasize that a single number is not enough to give account of energy throughput in agroecosystems. Instead we propose four interrelated EROIs which allow drawing a more differentiate picture of the sociometabolic profile of farming systems in a way aimed to bring into light the relationship between energy efficiency and agroecological performance of the underlying funds. These four EROIs are defined by including or excluding the flows of Biomass Reused or External Inputs in the denominator, and Final Produce or the Net Primary Production actually photosynthesized in the numerator (Figure 2.1).

The first couple of EROIs links the socio-economic and the ecological sides of agroecosystem functioning: meeting human needs (with Final EROI), and checking (with NPP EROI) whether they are satisfied without undermining vital funds that we deem to be related with the maintenance of soil fertility and biodiversity services. The NPP EROI[2] expresses the return on energy invested in terms of the actual Net Primary Production obtained from the photosynthesis within an agroecosystem vis-à-vis all internal and external socio-economic energy inputs:

$$NPP\ EROI = \frac{Net\ Primary\ Production}{Total\ Inputs\ Consumed} = \frac{NPP}{TIC}$$

This NPPEROI means looking at agroecosystems as human-colonized ecosystems. Nature continues to function in them, but it does so conditioned by the flow of internal and external energy carriers (TIC) and information that farmers invest. Given that[3]

$$NPP = UB + LP = UB + BR + FP - BP$$

we arrive at equation (2.1) that expresses the remainder of NPP EROI minus Final EROI per unit of TIC:

$$NPP\ EROI - Final\ EROI = \frac{UB + BR}{TIC} - \frac{BP}{TIC} \qquad Eq. (2.1)$$

The second term on the right side of this identity is only an accounting adjustment to avoid double counting Barnyard Produce (BP), whereas the meaning of this expression concentrates in the first term on the right side of Eq. (2.1). It bridges the two sides of energy throughput in agroecosystems in a way aimed to assess the resources left free for other species. It does so by means of two components: UB, which is the amount of biomass available for food chains for the rest of species; and BR, whose importance requires an integrated land-use management which in turn may increase land cover diversity and the number of habitats in agricultural landscapes (Margalef 2006; Marull et al. 2010). Both factors are expressed per unit of invested energy (TIC) or, in other words per unit of anthropogenic disturbance required to create and maintain an agroecosystem in a desired state. Our working hypothesis is that the greater the difference between NPP EROI and Final EROI the better the capacity to host biodiversity in an agroecosystem will be. While the verification of this hypothesis requires further research, we here

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[2]We use the 'actual' NPP values, not the 'potential' NPP_0 (the vegetation thatwould prevail in the absence of human landuse) usually accounted in the HANPP calculations (Krausmann et al. 2012).

[3]For the sake of simplicity, we are not treating here the flows of vegetable waste (LW) separately from BR (see Annex 1.B).

provide an energy assessment framework based on the four related EROI indicators which can support this type of research.

As TIC are composed of EI and BR, which can be substituted one another, Eg. (2.1) can also be written as:

$$NPP\ EROI - Final\ EROI = \frac{UB + BR}{EI + BR} - \frac{BP}{TIC} \qquad Eq(2.2)$$

According to our interpretation of equation (2.2), increasing EI would result in reducing the environmental space left available to other species per unit of human disturbance. At the same time, doing this at the expense of BR might also entail reducing the need for an integrated land-use management. Thus getting rid of BR per unit of TIC might lead to a decrease of the spatial heterogeneity and complexity of agro-forest landscapes, and a reduction in the species richness they can shelter. Relying on this working hypothesis, we propose using the proportions of UB, BR and EI as a proxy to assess in energy terms the conditions needed for other species to be hosted in agroecosystems.[4] According to this hypothesis, maintaining or improving biodiversity would require having enough UB and BR at the same time in the same area. A large amount of UB with a low diversity of habitats would lead to big populations of a limited number of species. Conversely, having a great share of BR per unit of TIC might translate into a great number of habitats that could remain empty if there is not enough biomass free of human colonization.

As shown in the previous chapter, in the Catalan case study shown in Figure 1 NPP_{act} EROI dropped from 3.18 in the traditional organic farm management c.1860 to 0.41 in the industrialized farm system of 1999. At the same time, the total amount of unharvested biomass grew by 19% from 290 TJ c.1860 to 346 TJ in 1999 mainly due to reforestation ensuing from rural abandonment. These results are well in line with findings from studies which have applied landscape ecology metrics to land-use maps in the same study area (Marull et al. 2010). They show a loss of agro-forestry landscape mosaics that may explain the decrease observed in the nearby populations of species that require land-cover diversity (e.g. Mediterranean orchids, butterflies, etc.), and the proliferation of

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[4] This approach to the role performed by loops of energy carriers inside an agroecosystem draws on some very basic principles of the functioning of living systems as dissipative structures that are able to maintain a dynamic stability far from thermodynamic equilibrium. Their internal cycles always make thermodynamic sense because thanks to them a living system can enhance its own complexity, increase its energy storage capacity, improve the energy throughput and start an ascendancy trend that decreases entropy dissipation (Prigogine and Stengers 1984; Ulanowicz 1986; Morowitz 2002; Ho and Ulanowicz 2005; Ho 2013).

others (e.g. boars) well adapted to the regrowth of abandoned woodlands that tend to behave like pests (Tello et al. 2014). This important issue requires a deeper study that we intend to carry out in future.

Final EROI, which is assessed at the exit side of an agroeocosystem, measures how much external and internal input is invested by a community of farm operators to get a given basket for human use (Fluck and Baird 1980; Pracha and Volk 2011):

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

Taken alone Final EROI has an important shortcoming, given that External Inputs (EI) are mixed with Biomass Reused (BR) in the Total Inputs Consumed (TIC). This aggregation disregards the role we deem BR plays as an investment to keep up the renewal of some vital funds that maintain soil fertility and biodiversity of agroecosystems. In order to solve this concealment TIC can be broken down into its two components, BR and EI. This gives way a pair of interrelated EROIs, the External and the Internal Final EROI.

External Final EROI is defined as the ration of external inputs to the output of final produce, which comprises all biomass products for human consumption leaving the agro-ecosystem (Figure 2.1):

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

This EROI links the agroecosystem with the rest of the energy system of a society (Carpintero and Naredo 2006; Pracha and Volk 2011). Recall that EI are composed of farm labour (L) and other inflows from the farming community or the rest of society (ASI). In organic agroecosystems with low societal inflows External final EROI approaches the meaning of the ‘Podolinsky Principle’—according to which the labour performed by farmers has to provide an energy surplus to the rest of society (Martinez-Alier and Naredo 1982; Podolinsky 2004; Burkett and Foster 2008; Martinez-Alier 2011). A declining External Final EROI also expresses the increasing dependence on external societal inflows in increasingly industrialized farm systems. It also allows a subsequent estimation of how many non-agricultural people a certain farm communities is potentially able to support, and becomes very relevant for evaluating the agricultural component of the ‘Law of minimum EROI’ put forward by Hall et al.(2009; Hall and

Klitgaard 2012)—which states that for any social system to survive it must attain a minimum energy return (Tainter 1988).

The main shortcoming of External Final EROI is that it neglects the significance of biomass reused (BR) for the energy profile of agro-ecosystems. This is overcome by a complementary measure, the Internal Final EROI. This EROI expresses the investment made by the farm-operators in keeping up the renewable funds of an agroecosystem:

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

By combining these three EROI measures, we can identify different pathways to increase the energy return on investment of farming systems taking into account their different impacts on agroecosystem services and socioeconomic outputs. As organic farm systems nearly always bear greater internal flows per unit of output, just by getting rid of them any industrialized farm management may attain greater internal returns per unit of Final Produce (FP). Given that EI can substitute for BR and vice versa, three possible strategies for increasing agricultural energy yields appear: 1) attain greater output per unit of TIC, whether internal or external, which means increasing the joint energy efficiency; 2) reduce inputs consumed per unit of output by relying on internal inputs and saving external inputs; and 3) reduce inputs consumed per unit of output by relying on external inputs and saving internal inputs. Along the sociometabolic transition from past organic to industrialized farm systems there has been a substitution trend from internal towards external inputs. This leads us to interrelate Final EROI with its respective internal and external returns so as to draw a broader energy profile of agricultural systems along this historical change.

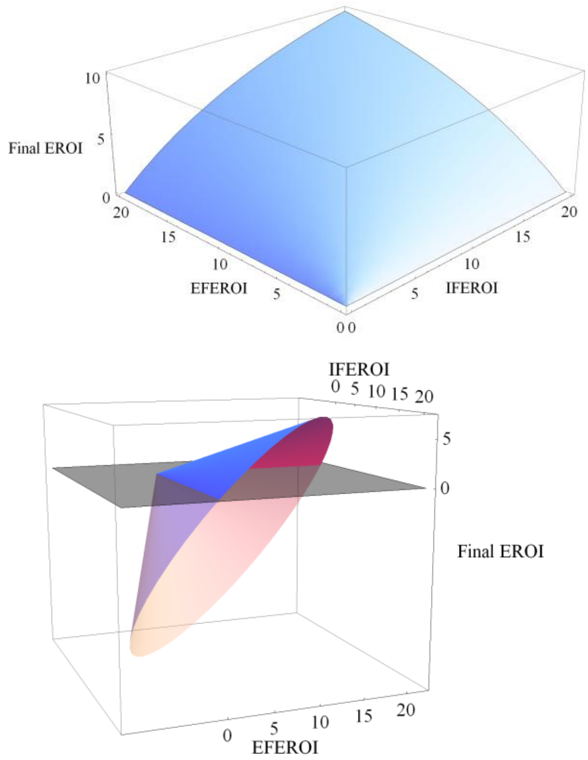
3. Relating Final EROI with its internal and external returns

Final EROI is related with its returns internal (IFEROI) and external (EFEROI) according to the following equation (2.3), that can easily be found by substitution as explained in the previous chapter:

$$Final\ EROI\ (FEROI) = \frac{EFEROI \cdot IFEROI}{EFEROI + IFEROI} \qquad \text{Eq (2.3)}$$

Expression (2.3) is the equation of the quadratic surface shown in Figure 2.2, which happens to be a cone centred at the origin (left side of Figure 2.2) or, to be more precise, a portion of a cone (right side of Figure 2.2), as the values of EFEROI and IFEROI can only be positive.[5]

Figure 2.2. Graphical representation of Final EROI as a function of EFEROI and IFEROI.



Source: our own.

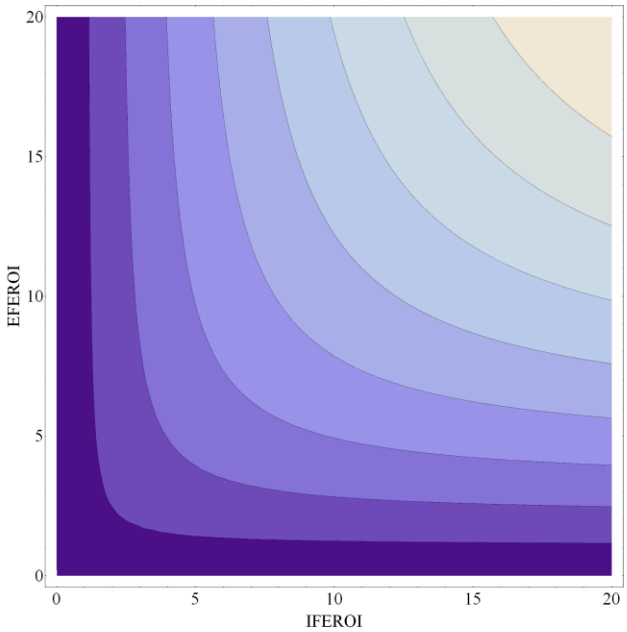
This function incurs in decreasing returns at any point: to get any increase in the joint Final EROI proportionally greater increases in either internal or external returns or both are needed. In fact, at any point $(x, y)$of the surface, the directional

[5] In fact, equation (3) can be rewritten as $z = \frac{xy}{x+y}$ or equivalently $-xy + xz + yz = 0$. In terms of matrices, $(x \quad y \quad z)\begin{pmatrix} 0 & -1/2 & 1/2 \\ -1/2 & 0 & 1/2 \\ 1/2 & 1/2 & 0 \end{pmatrix}\begin{pmatrix} x \\ y \\ z \end{pmatrix} = 0$. The previous symmetric matrix has eigenvalues -1 with multiplicity 1, and $1/2$ with multiplicity 2. Hence the matrix diagonalizes and equation (1) reduces to $x^2 = (y^2 + z^2)/2$, which is the equation of a cone. This cone is trivially centred at point (0,0,0). Vector $(1,1,-1)$ is an eigenvector of eigenvalue -1, therefore the axis of the cone has its direction.

derivative in the direction of the gradient is $\frac{x^4+y^4}{(x+y)^4}$ is strictly smaller than 1 for all points with no null coordinates, and equals 1 when either coordinate is 0.

If we consider Final EROI as a function of IFEROI and EFEROI then Figure 2.3 shows the contour lines, or isoquants, of this function. It is easy to show that these curves are hyperbolae (in fact, they are conic sections in the horizontal direction, which forms an angle with the axis of the cone smaller than the one of the generatrix). When restricted to one of such curves, any increase or decrease of one of the partial EROIs (internal or external) can be compensated by a decrease or increase of the other, respectively. The isoquants being hyperbolae, the relation between the two variations is inversely proportional. The proportional factor depends on the eccentricity of each isoquant.

Figure 2.3.Isoquants of Final EROI as a function of EFEROI and IFEROI

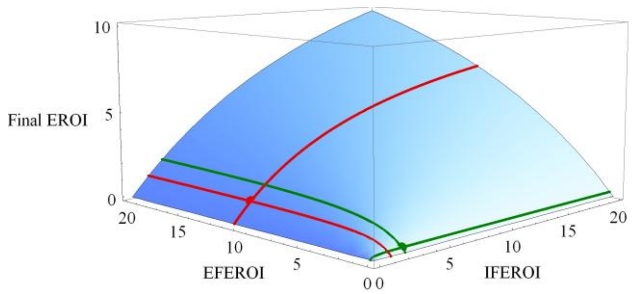


Source: our own.

As we are interested in the role played by external flows and internal reuses in the energy performance of agricultural systems, we can delve deeper into this analysis in order to reveal how variations in EFEROI and IFEROI affect the position adopted by Final EROI along the corresponding conic surface in terms of the underlying function that relates Final Produce (FP) with internal (BR) and external (EI) inputs. For the time being all we can say is that assuming a constant Final Produce, the variation of EFEROI (relative to IFEROI) is inversely proportional to that of EI (relative to BR). Unfortunately, the function –or perhaps 'functional' according to (Georgescu-Roegen 1971)— relating FP with BR and EI is too complex to be determined. In agroecosystems any internal or external biophysical flow interacts with a set of funds which can only bring about a final produce within a limited range of variation in yields and in a discontinuous manner. What really matters are the emerging properties arising out of the whole network of synergistic links of flows established among a myriad of funds working together to attain a joint performance and outcome—and that is the main focus of agroecology as a science (Altieri 1989; Gliessman 1998; Snapp and Pound 2008).

An empirical workable way to deal with such a complex issue is to plot the various combinations of IFEROI and EFEROI existing behind any given Final EROI attained by an agricultural system, in order to cluster them around characteristic typologies. Figure 2.4 shows the organic farm systems existing in Vallès County study area c.1860 compared with the industrial one in 1999. It depicts the data as points in the conic surface, as well as their isoparametric curves.

Figure 2.4.Plotting the Internal and External final energy returns behind the Final EROI



Note: Values for c.1860 are in red and for 1999 in green. Source: our own.

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

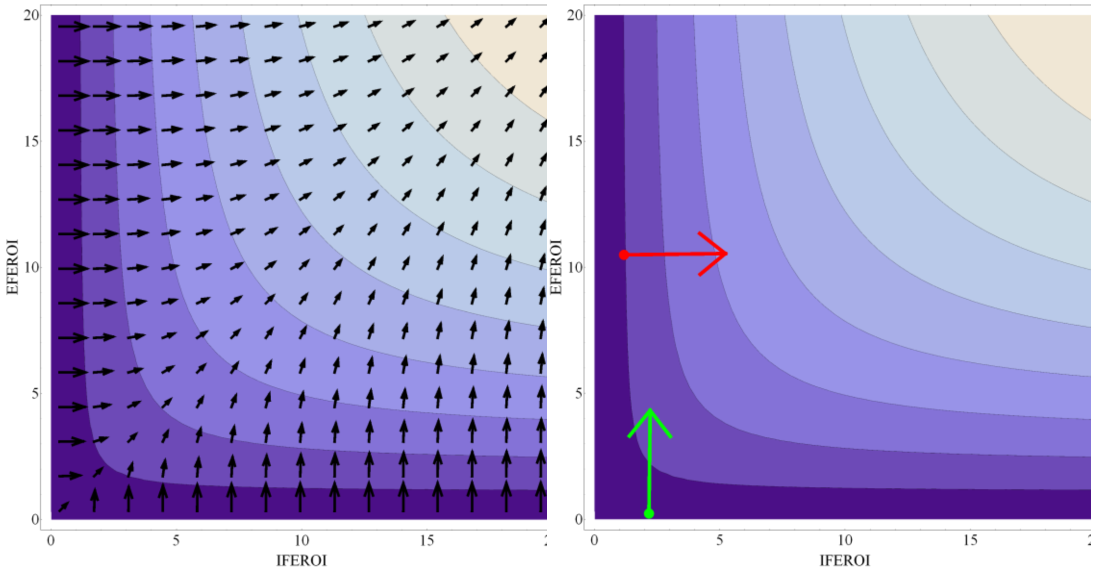
External Final EROI was extremely low and this could be compensated only to some (minor) extent by reducing the internal flows of BR.

The first of these strategies is currently labelled ‘Low External Input Technology’ (LEIT) and fits well with an agroecological approach for sustainable agriculture (Tripp 2008)—given that in low-input agriculture, where the harvested flow of biomass remains within the range of natural turnover, farm activities interfere only to a limited extent with the system of controls regulating matter and energy flows in ecosystems (Giampietro 1997a). The opposite strategy corresponds to the paths taken by industrialized agricultural systems based on ever greater external inputs, mainly fossil fuels.

4. Assessing improvement pathways of Final EROI

The quadratic surface showing the relationships of Final EROI with its external or internal returns can also be used to find out optimal improvement pathways. Figure 2.5 presents in the left side the gradient vector at each point that indicates for each pair of values (EFEROI, IFEROI) the direction to which the function (2.3) can be optimally improved. Besides optimal directions, the left figure also depicts the improving capacity at each point by means of the length of the gradient vector.

Figure 2.5.Directions and comparative lengths of the increase on energy efficiency



Note: The figure on the left shows the potential gradient vectors for optimal improvements. The figure on the right shows the gradient vectors for optimal improvements specifics for the Catalan study area c.1860 (red) and 1999 (green).Source: our own.

We can observe that potential improvements are higher if Final EROI is lower, or/and when the combination of EFEROI and IFEROI is skewed. All these pathways led towards points of higher Final EROIs with lower improvement capacities that tend to approach the ones along the diagonal with higher diminishing returns (where Final EROI = $\frac{\text{EFEROI}}{2}$ = $\frac{\text{IFEROI}}{2}$, and $\frac{\text{EI}}{\text{BR}} = 1$).

This way, we can map the improving capacity of Final EROI in agroecosystems by following the optimal combination of internal or external returns, and compare the theoretical possibilities with available empirical data (Figure 2.5). In the Catalan example c.1860 the gradient vector indicates that a small increase of Internal EROI would have resulted in a large increase in Final EROI, given that the slope of the isoparametric curve representing its $\frac{\text{FP}}{\text{BR}}$ ratio attains in this point the highest return compared with the other—meaning that the internal return had a much higher impact because external inputs were then comparatively small.

One way to improve the $\frac{\text{FP}}{\text{BR}}$ ratio c.1860 was to further improve the integrated land-use management with increasing livestock breeding and thus available manure per unit of land, or by reducing losses in manure heaps and other barnyard services. To what extent can this be considered feasible in the Valles County c.1860? We know that this highly intensive farm system heavily relied on biomass reuse: In order to keep up soil fertility, farmers had to feed livestock by growing fodder crops and reusing a large fraction of agricultural by-products, sowing green manures, and burning or burying a large amount of forest and scrub biomass on cropland (Cussó et al. 2006a; Cussó et al. 2006b; Garrabou et al. 2010; Tello et al. 2012). Land-use intensification, mainly driven by vine-growing specialization (Badia-Miró and Tello 2014), seems to have increased agroecological stress leading this preindustrial farm system towards lower energy returns—albeit nearly to one as we saw in previous chapter. Perhaps a lower population density and land-use intensity would have also led to higher IFEROI and Final EROI, thanks to a reversal of the well-known sequence towards a growing farming activity on the available land that gives way to diminishing returns (Boserup 1965). However, adopting more extensive land uses would entail forcing the unemployed rural population to emigrate.

There was a third pathway to increase the $\frac{\text{FP}}{\text{BR}}$ ratio: restraining the labour-intensive effort by reducing the amount of BR per unit of final produce obtained while keeping high land-use intensity. Whereas the first option would rely on improving agroecological management, and the second would entail expelling labourers from the land, the latter would led to unsustainable paths—e.g. by mining soils not properly fertilised.[6] The dilemma illustrates the difficult choices many past organic farm systems faced just before the onset of agricultural industrialisation, when the pressure to increase output arising from local population growth and urban markets grew. This issue deserves a comparative analysis about the trade-offs and limits between land-use intensity and sustainability of farm systems (Erb 2012; Krausmann et al. 2012).

5. Decomposition analysis of the historical shifts in Final EROI

Another way to delve into the historical changes experienced by agricultural systems is disentangling the role played by the internal or external energy returns in any shift experienced by Final EROI. This can be achieved by a decomposition analysis, considering that *FP* = *h*(*EI*, *BR*), where *h* is a function we know that exists but the expression of which remains unknown. Using a simpler notation for the variables, the situation is written:

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

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

According to the chain rule, we know that

$$\frac{\partial w}{\partial x} = \frac{\partial w}{\partial x}\frac{\partial x}{\partial x} + \frac{\partial w}{\partial y}\frac{\partial y}{\partial x} + \frac{\partial w}{\partial z}\frac{\partial z}{\partial x} = \frac{\partial w}{\partial x} + 0 + \frac{\partial w}{\partial z}\frac{\partial z}{\partial x} = \frac{-z}{(x+y)^2} + \frac{1}{x+y}\frac{\partial z}{\partial x} = \frac{-z+(x+y)\frac{\partial z}{\partial x}}{(x+y)^2}.$$

Analogously,

$$\frac{\partial w}{\partial y} = \frac{-z+(x+y)\frac{\partial z}{\partial x}}{(x+y)^2}.$$

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[6] In our first energy balance for the entire Vallès County we got a Final EROI of 1.41 c.1870 (Cussó et al. 2006b). Then, in the five municipalities of our study area we obtained a Final EROI of 1.67 c.1860 (Cussó et al. 2006a). After a better assessment of the fertilising methods applied (Olarieta et al. 2011; Tello et al. 2012), it dropped to 1.23 (Tello and Galán-Del-Castillo 2013). Here and in previous chapter we have carried out a thoroughly revision not only using better sources and new accountancy rules, but performing a stricter control in order to assess that the energy yields we obtain as a reference were not attained at the expense of soil fertility, deforestation or livestock malnutrition (Marco et al.). As a result, the Final EROI c.1860 dropped again to 1.05. It seems likely that the actual energy yields of this highly intensive organic agriculture led to some degree of soil mining and deforestation).

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

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

Since the function *FP* = *h*(*EI*, *BR*) is unknown, we need to estimate the value of the partial derivatives of z with respect to x and y. The only approximation possible, from the available data, is trivial:

$$\frac{\partial z}{\partial x} \approx \frac{\Delta z}{\Delta x}, \frac{\partial z}{\partial y} \approx \frac{\Delta z}{\Delta y}.$$

Then, given two situations $s_1 = (x_1, y_1, z_1, w_1)ands_2 = (x_2, y_2, z_2, w_1)$, we get:

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

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

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

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

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

We can hence write:

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

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

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

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

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

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

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

Effect of variation in BR $= \frac{-\frac{FP_1+FP_2}{2}\Delta BR + \frac{EI_1+EI_2+BR_1+BR_2}{4}\Delta FP}{(EI_1+BR_1)(EI_2+BR_2)}$ Eq. (2.4)

Notice that in this kind of decomposition analysis negative or positive results only mean that the corresponding partial variation has moved in the same direction, thus reinforcing it, when the sign is the same as the variation being decomposed. Inverted signs exert a counterbalancing effect. In our Catalan case study, Final EROI dropped from 1.05 circa 1860 to 0.21 in 1999. Now we want to assess the role played by the variation of internal reuses and external flows, and their corresponding partial energy returns, in the following variation experienced in Final EROI: $\left(\frac{0.21-1.05}{1.05}\right)\times 100 = -80.2\%$.

Applying equation (2.4) we obtain that the variation of −0.84 EROI points (or −80.2%) experienced between Final $EROI_{1860}$ and Final $EROI_{1999}$ would have been explained by a sharp decrease in the corresponding variation between EI_{1860} and EI_{1999}, which is equal to

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

$$= \frac{-\frac{246{,}634+316{,}105}{2}\,1{,}345{,}664 + \frac{23{,}500+1{,}369{,}164+210{,}732+145{,}304}{4}\,69{,}471}{(23{,}500+210{,}732)(1{,}369{,}164+145{,}304)}$$

$= -0.98$

This represents 116.3% of the total variation. However, the effect driven by the variation of EI was counteracted by the corresponding variation between BR_{1860} and BR_{1999}, which is equal to

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

$$= \frac{-\frac{246{,}634+316{,}105}{2} - 65.428 + \frac{23{,}500+1{,}369{,}164+210{,}732+145{,}304}{4}\ 69{,}471}{(23{,}500+210{,}732)(1{,}369{,}164+145{,}304)}$$

$= 0.14$

This represents -16.3% of the total decomposed variation. Combining both opposite effects we can explain the whole variation experienced, which is $-0.98 + 0.14 = -0.84$ Final EROI points. The result reveals that the decrease in Final EROI between 1860 and 1999 was mainly due to a big increase in External Inputs, coming directly from fossil fuels or indirectly through feed imports for livestock breeding in feedlots, which caused External Final EROI to decline significantly—notice that EI_{1999} was 2.2 times larger than the total NPP_{act} in the study area! However, the effect was counteracted to some extent by a parallel reduction in internal flows of Biomass Reused and the ensuing increase of Internal Final EROI. Had such a counterbalancing effect not taken place, the drop in Final EROI would have been even higher. The result brings to light an important feature: the grater the change from circularity to linearity in the energy flows going through an agroecosystem, the more important this decomposition analysis becomes.

6. Concluding remarks

In this chapter we presented a method to relate internal and external returns of agricultural systems, by drawing their energy profiles and yields within a range of possible improvement pathways. It also allows disentangling the respective weights of these internal and external returns in any shift of Final EROI. We deem that this approach becomes a very revealing tool in order to conceive better agricultural farm managements, public policies and consumer preferences in a world that faces a worrying crossroads for food security arising from peak oil and climate change(Mulder and Hagens 2008; Hall et al. 2009; Giampietro et al. 2011;

Arizpe et al. 2011; Hall 2011; Murphy et al. 2011; Manno 2011; Pracha and Volk 2011; Scheidel and Sorman 2012; Giampietro et al. 2013). This decomposition analysis can be used to gain a better understanding of the sociometabolic transitions from past traditional organic farm systems to industrial ones, and to gain useful knowledge for developing more sustainable agricultures(Fischer-Kowalski and Haberl 2007; Smil 2010; González de Molina and Toledo 2011) in future.

Gathering more information on Final EROI, IFEROI and EFEROI from a broad variety of farming systems in different world regions and from different time periods would allow plotting them into three-dimensional graphs like our Figures 2.4 and 2.5, in order to observe how they cluster or not in some regions of the conic surface and the corresponding isoparametric curves. International and historical comparisons can be performed this way in order to test whether organic and industrialized farm systems have tended to a specific pair of opposite 'attractor situations'. By attractor situations we mean here a set of links established between socioeconomic drivers (e.g. the structure of relative prices of factors and goods in the markets reinforced by the prevailing landownership or institutional settings), and the sociometabolic profile and functioning of agroecosystems, that become more likely than others. Societies can overcome these situations by moving to other energy profiles and performances, but only by changing the underlying set of linkages between agroecological functioning and socioeconomic drivers.

The existence of such attractor situations has been suggested by Giampietro(1997a). Once industrial agricultural systems start relying in external inputs coming from fossil fuels in search of greater labour and land productivity, they also tend to engage in monocultures and reduce internal reuses. This entails a reduction in agroecosystem complexity that undermines the regulatory services provided by biodiversity. This in turn requires replacing them by other artificial controls, such as pesticides and mechanical work that increase again the amount of external inputs. This feedback drives the energy profile of industrialized agricultural systems towards a high-input combination of lower EFEROIs only partially compensated by higher IFEROIs, giving way to a big loss in Final EROIs—as seen in our Catalan example. This sounds very familiar to anyone aware of the challenges and opportunities that agriculture now faces worldwide. Through clustering analysis applied to our decomposition analysis of agricultural energy profiles we can test whether this working hypothesis is true or not.

Annex 1.A. Disaggregation of BR (Biomass Reused) flow for Vallès c.1860

Table 1.A shows the disaggregation of the BR flow c.1860. Organic matter returned to the soil either fresh or burnt was 55%, 2% were seeds and 43% was biomass reused in barnyards as feed, fodder, grass and crop by-products eaten by livestock or straw used in stall bedding. The former was used to keep soil biodiversity and fertility, whereas the latter was directly led to high cropland and farmland diversity. The production of fodder and feed involved 42% of cropland area, while at the same time livestock was feed in pastures (21% of farmland area) or in the grass layers below open forests and other uncultivated land, thus leading to maintain landscapes mosaics. Besides these direct contributions to belowground biodiversity and aboveground diversity of vegetal covers there were others indirect, such as crop rotations, stubble grazing or fallow weed grazing, which required keeping vegetal hedgerows that in turn enhanced the mosaic pattern in agricultural landscapes.

Table 1.A. Disaggregation of the BR (biomass reused) flow for Vallès c.1860.

BIOMASS REUSED 210732 (100%)	FARMLAND BIOMASS REUSED 120728 (57%)	SEEDS	4307 (2%)
		BURIED BIOMASS FROM CROPLAND	79798 (38%)
		HORMIGUEROS 36622 (17%)	FROM PRUNING 21489 (10%)
			FROM FIREWOOD 15133 (7%)
	BARNYARD BIOMASS REUSED 90005 (43%)	FEED	9126 (4%)
		FODDER	12870 (6%)
		CROP BY-PRODUCTS	30229 (14%)
		GRASS	24577 (12%)
		STALL BEDDING	9322 (4%)
		OTHER FROM WOODLAND	3882 (2%)

Note: Numbers are in GJ, percentages are weight over total BR flow.Source: (Marco et al.).

Annex 1.B. Value of the flows

All energy carriers have been valued by their Enthalpy in Gross Calorific Values when they came from inside the agroecosystem. In all external inputs the embodied energy required to place them within the system has been added. Human labour has been accounted by the energy content of food metabolized while working in the farm system, and embodied energy has been added whenever the components of this food basket came from outside. The internal Barnyard Services (draft power, manure) appear as a reminder, but are not included in TIC and EROIs to avoid double counting.

Table 1.B. Funds and Energy flows of farm systems in the Catalan case study c.1860 and in 1999

		c.1860	1999	units
	Inhabitants	8,853	11,669	inhabitants
	Population density	65.6	86.5	inhab./km^2
	agricultural active population	1,933	276	AWU*
	heads of family working in agriculture	68.9%	n.a.	
	Total area	134.9		km^2
	Farmland	12,011	11,669	ha
	Cropland	5,902	3,745	ha
	vegetables & fruit trees in gardens	179	206	ha
	irrigated annual crops	314	123	ha
	rain-fed annual crops	1,724	3,130	ha
	vineyards	3,235	62	ha
	olive groves	450	224	ha
	Pastureland	2,555	827	ha
	Woodland & scrub	3,623	7,097	ha
	Livestock density per unit of farmland	8.4	152.1	LU500/km^2
NPP	Actual Net Primary Production estimated	744,291	622,059	GJ
UB	Unharvested Biomass	289,965	345,885	GJ
LP	Land Produce	454,326	276,175	GJ
LP	LP—Cropland	260,647	262,023	GJ
LP	LP—Pastureland	24,577	993	GJ
LP	LP—Woodland& scrub	169,103	13,158	GJ
BP	Barnyard Produce	3,040	192,908	GJ
TP	Total Produce	457,366	469,082	GJ
BR	Biomass Reused	210,732	145,304	GJ
FBR	Farmland Biomass Reused	120,728	6,168	GJ
FBR	FBR—seeds	4,307	2,350	GJ
FBR	FBR—buried biomass	79,799	3,818	GJ
FBR	FBR—biomass burnt& ploughed (‘hormigueros’)	36,622	0	GJ
BBR	Barnyard Biomass Reused	90,005	139,136	GJ

BBR	BBR—feed crops	9,126	38,317	GJ
BBR	BBR—fodder crops	12,870	32,924	GJ
BBR	BBR—crop by-products to animal feeding	30,229	25,273	GJ
BBR	BBR—grass	24,577	993	GJ
BBR	BBR—other animal feedingfrom woodland	3,882	0	GJ
BBR	BBR—stall bedding	9,322	41,629	GJ
FP	Final Produce	246,634	316,105	GJ
FP	FP—food and fibre	42,301	206,841	GJ
FP	FP—food	26,747	205,566	GJ
FP	FP—grape juice to make wine	11,346	541	GJ
FP	FP—edible forest products	1,376	0	GJ
FP	FP—fibre (hemp, wool, hides)	2,832	734	GJ
FP	FP—other industrial crops (rape)	0	6,284	GJ
FP	FP—grapevine & olive oil pomaces sold outside	0	1,056	GJ
FP	FP—forest timber	4,144	13,158	GJ
FP	FP—forestfirewood	144,569		
FP	FP—pruning & vines or trees removed to firewood	54,206	109	GJ
FP	FP—animal feed sold outside	0	88,656	GJ
BS	Barnyard Services	38,821	2,651	GJ
BS	BS—manure	35,296	2,651	GJ
BS	BS—draft power	3,525	0	GJ
BW	Barnyard Waste	0	291,936	GJ
L	Labour	3,648	3,320	GJ
ASI	Agroecosystem Societal Inflows	19,853	1,370,197	GJ
FSI	FSI—human garbage and sewage	19,853	0	GJ
FSI	FSI—machinery	0	213,941	GJ
FSI	FSI—herbicides	0	15,281	GJ
FSI	FSI—chemical fertilisers	0	12,670	GJ
FSI	FSI—seeds bought from outside	0	1,660	GJ
FSI	FSI—water pumping (electricity)	0	4,387	GJ
BSI	Barnyard Societal Inflows	0	1,122,258	GJ
BSI	BSI—animal feed & fodder bought from outside	0	999,315	GJ
BSI	BSI—energy consumed in feedlots (fuel & electricity)	0	122,943	GJ

Source: (Marco et al.).*AWU: full-time Agricultural Working Units a year.

Chapter 3. The sad hoax. Comparison of the two energy balances c. 1860 and 1999 in the Vallès county (Barcelona)

"A whole generation of citizens thought that higher efficiencies in using the energy of the sun had arrived. This was a sad hoax, for people of the developed world no longer eat potatoes made from solar energy."

(Odum, 2007[1970]: 190).

1. Aims and scope

1.1. The diminishing energy returns of industrial agriculture

Although the increase in yields per hour of work and economies of scale occurred in a paradigmatic industrial monoculture, paradoxically (or not) it is inefficient in energy terms. Following the idea of Lotka (1956), Ecological Economists used to distinguish between 'endosomatic' and 'exosomatic' use of energy by humans. The endosomatic use of energy is that used by human bodies, i.e. the intake of food, between 1500-2500 kcal·day^{-1} or 2.3-3.8 GJ·yr^{-1} on average per person. Examples of exosomatic uses of energy are energy used for cooking, heating, transport and examples of energy carriers are biomass, coal or oil. While all humans have similar endosomatic use of energy, the importance of exosomatic use varies depending on a number of factors, foremost income (EJOLT 2012).

In the second step of the industrial metabolic transition, mature industrial economies have a flow of exosomatic energy between 200 and 450GJ·yr^{-1}, mostly from oil and natural gas (Krausmann and Fischer-Kowalski 2013). This situation is replicated in industrial agriculture, as agroecosystems are fuelled with fossil exosomatic energy. The amount of energy used in industrial agriculture is so high that although the energy output increased in comparison with traditional agriculture, in relation to its energy inputs it has decreased. In the words of Martinez-Alier: "From this point of view, modern agriculture is less productive"

(Martinez-Alier 2011) as it incurs diminishing returns[1](Ho and Ulanowicz 2005; Martinez-Alier 2011).

In pre-industrial agricultures, low energy efficiencies indicated famine risks as the main inputs were from endosomatic energy i.e. human work and the exosomatic uses were mainly from organic sources (e.g. livestock, biomass). Logically this is not the case when the main input is exosomatic energy from fossil sources, but the vulnerability of this model increases as long as finite stocks of oil (Campbell and Laherrère 1998; Deffeyes 2001) or other materials such as phosphorous (Cordell and White 2011) peak. At the same time industrial agriculture lives together with some agricultural practices getting high yields per hectare following Low External Input Technologies (LEIT) (Tripp 2008) with higher energy returns (Dalgaard et al. 2001; Martinez-Alier 2011).

From the point of view of Environmental History there is not one historical pathway designed by science and technological applications, but a multiplicity of dynamic equilibriums of human-nature interactions concerning different levels of sustainability (González de Molina and Toledo 2011). Could past practices that were more sustainable than current ones be recovered? Was there another way for the European societies at the end of the nineteenth century rather than developing an agriculture with decreasing energy returns?

1.2. The loss of landscape heterogeneity

The change towards an industrial agrarian metabolism had a variety of effects in the Mediterranean landscape. This has been studiedsince the decade of 1980s, when Spain entered in the Common Agricultural Policy of the European Union. These changes can be summarised into two: the cultivation ceased in the least productive areas and the intensification of production in the more fertile lands (Perez 1990; González-Bernáldez 1991; Sancho Comins et al. 1993).

Recent studies added landscape metrics to measure the relationship between landscape and the modification of agricultural practices specifically in Mediterranean regions. Here, the decline of agro-forestry in the mountainous areas lead to a homogenisation and fragmentation of the landscape (Bielsa et al. 2005). Moreover, the general decrease in livestock numbers and the change in population types (with a dramatic decrease of sheep) contributed to the loss of herbaceous covers at the entrance to scrubland and woodland, which in turn

[1]Although the diminishing EROI in agriculture is a general trend in the long run, there could be discontinuities in the short run (Pracha and Volk 2011).

decreased the livestock potential of the system and increased the risk of fires (Lasanta-Martínez et al. 2005).

The same trend was found for semiarid Mediterranean landscapes where the socioeconomic variables promoting pre-industrial agricultural practices created more heterogenic landscapes than the ones promoting industrial agriculture (De Aranzabal et al. 2008). In the Mediterranean coastal areas, the process of change was even more dramatic due to urban sprawl, growth of low-density residential area, agricultural abandonment and transport infrastructures (Parcerisas et al. 2012).

Therefore, in Mediterranean areas the industrialisation of agriculture has gone hand in hand with the loss of landscape heterogeneity, i.e. loss of different habitats. In the northeast corner of the Iberian Peninsula this was characterised by loss of pastures and cropland in highlands, urban sprawl in coastal areas and concentrations of cropland in the plain areas. At field scale, the decrease of hedgerows and cultivars also contributed to the homogenisation of cropland areas, a trend found globally (Gliessman 1998). Practices of industrial agriculture both at local scale e.g. cultivating monocultures of high-yield varieties, or at landscape scale e.g. increasing field size or destroying edge habitats, decrease biodiversity with the ensuing loss of ecosystem services (Altieri 1999; Tscharntke et al. 2005).

The importance of biodiversity is well-known for its functional aspect in human activities, providing ecosystem services such as pollination enhancement and pest control (Loreau et al. 2001; Cardinale et al. 2012; Nicholls and Altieri 2012), or in making ecosystems and agroecosystems resilient, i.e. to recover from disturbances (Bengtsson et al. 2003; Naeem et al. 2012). The last is very important in Mediterranean areas as they are exposed to drastic seasonality (Zamora et al. 2007).

As there are niche differences among species, landscape heterogeneity maintains the diversity of between-units or edge species—beta diversity—which together with the within community or inner species—alpha diversity—shape the total or regional diversity—gamma diversity—(Loreau 2000). Hence, landscape structures moderate the biodiversity patterns in a nested hierarchy of multiple scales and influence population, community and ecosystem processes. However the combined effect of habitats loss and land fragmentation as well as the role of beta diversity in overall diversity have yet to be explored, as well as the role of alpha and beta diversity. In that sense, specific statements relating biodiversity conservation and landscape patterns are as yet formulated as hypotheses (Tscharntke et al. 2012). Therefore, the general recommendation for biodiversity conservation is to add dynamic reserves—areas of moderate disturbance regimes—e.g. agricultural land, to the static biodiversity reserves, e.g. natural parks (Bengtsson et al. 2003).

Decades ago, Margalef summarised the dialectical relation between exploitation and conservation: "To sum up, exploitation as opposed to conservation is a great dilemma, and there is probably no solution that could satisfy the aims of both. Ecology can devise the most efficient means of exploitation, but conservation requires non-interference with nature, even refraining from "protecting" her. Probably the best solution would be a balanced mosaic or 'rather a honeycomb', of exploited and protected areas." (Margalef 1968). Currently, most ecologists agree with this idea of mosaic, which in general consists on leaving aside non cultivated land within large cropland areas (land sparing) to protect biodiversity at landscape scale (Fischer et al., 2008; Phalan et al., 2011).

Nevertheless, agriculture has not always been necessarily confronted with biodiversity issues, as it could create edge habitats, as was the case of pre-industrial European agroforestry areas, i.e. planting food or forage crops along with trees (Pimentel et al. 1992; Eichhorn et al. 2006; Plieninger et al. 2006) or pastures, hay meadows or moorlands of mountain areas (MacDonald et al. 2000). However, they tended to be abandoned along with the industrialisation of agriculture(González-Bernáldez 1991; Poyatos et al. 2003; Lasanta-Martínez et al. 2005; Geri et al. 2010) with the ensuing homogenisation of landscape and loss of beta diversity. Some examples are the loss of birds, orchids and dung beetle species in Mediterranean landscapes (Zamora et al. 2007; Sirami et al. 2008; Tello et al. 2014) or the loss of plant species in Swiss and Swedish grasslands (Fischer et al., 2008; Gustavsson et al., 2007).

What is the relation between the diminishing energy returns and the loss of landscape heterogeneity and so biodiversity, experienced by Mediterranean farm systems throughout the Socio-Ecological Transition? Although industrialisation of agriculture went hand in hand with biodiversity loss, some agricultural practices can enhance beta diversity and ecosystem services by creating edge habitats such as hedgerows or fallows (Matson 1997; Bianchi et al. 2006). Also less intensive agricultural practices which lay in functional biodiversity instead of external inputs such as those followed in organic farming which are related with higher levels of biodiversity (Gliessman 1998; Altieri 2002; Gabriel et al. 2006).

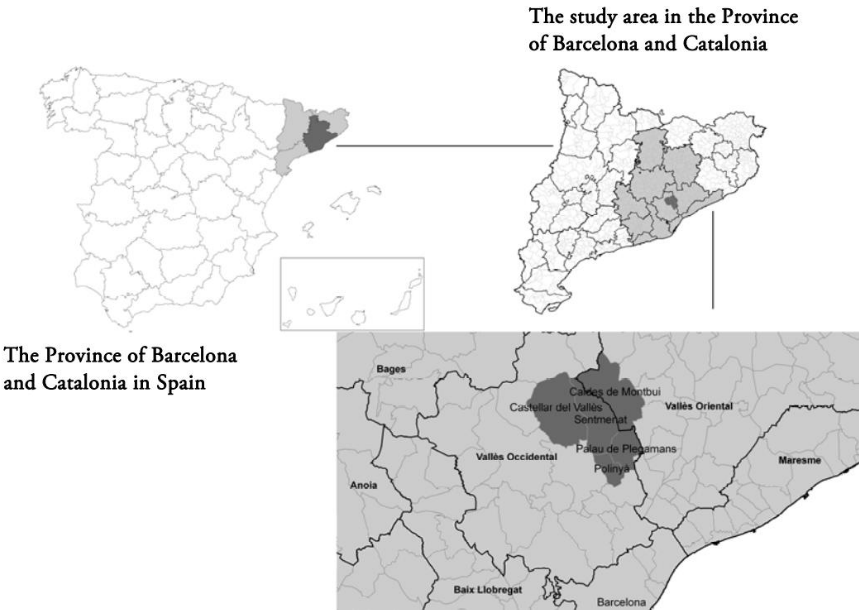
Yet, whatever the agrarian metabolism, the food production will always be dependant on a number of ecosystem services strongly linked to biodiversity such as fresh water, pollination, biological pest control, N fixation, etc., that cannot be substituted by technical capital (Giampietro 1997a).

2. Main methodological aspects

As will be explained in the next section, we started studying Sentmenat municipality c.1860 due to the high amount of available data. For this case study, we added one more area under the Marquis of Sentmenat property, Palau-solità-i-Plegamans and three municipalities more, Polinyà, Caldes de Montbui and Castellar del Vallès.

Around twenty years ago a few Spanish historians specialising in Agricultural History found a confluence with Environmental History when they started to study the historical change of landscape under the umbrella of the *Sociedad Española de Historia Agraria (SEHA)*. See part of this discussion summarised in Tello (1999). As will be explained, it is a matter of coincidence and good luck that we have good cadastral information c.1860 of the adjacent municipalities. As a whole they describe a triangle from the mountainous area of *Serralada Prelitoral* to the centre of the Vallès plain, see Figure 3.1.

Figure 3.1. Location of the five municipalities in the study area (West and East Vallès counties in the Province of Barcelona, Catalonia and Spain).



Source: from Marull et al. (2008a)

All this information constituted a prolific source for historiography and today we have a number of studies available in a variety of interrelated topics. Some examples are: diets and nutritional differences between rural and urban populations (Cussó and Garrabou 1992; Cussó and Garrabou 2004; Cussó 2009; Cussó and Garrabou 2012); land property and inequality (Garrabou et al. 2010; Badia-Miró et al. 2010; Badia-Miró and Tello 2014); change on land uses (Tello et al. 2006; Tello et al. 2008a; Tello et al. 2008b); landscape and landscape metrics (Tello and Marull 2006; Marull et al. 2008a; Marull et al. 2008b; Marull et al. 2010); historical fertilising methods (Olarieta et al. 2011; Tello et al. 2012); and even energy flows in agriculture (Cussó et al. 2006a; Cussó et al. 2006b).

Why was then needed another study on the area? At the beginning of my Ph.D., I tried to start a new case study for studying the energy flows in agroecosystems, when I realised that the methodology of the studies for this area was not clear enough to be replicated. Still, the case studies already done studying energy returns of agricultural systems in Spain were comparable enough to draw a very general trend: as long as agriculture had become industrial, the external, fossil based, energy flows increased, thus reducing the energy efficiency (Carpintero and Naredo 2006). Yet, it was easy to see that they were not considering the same flows when calculating the Return on Energy inputs in agrarian systems, the same was stated for the agri-food systems by Infante-Amate et al. (2014).

Earlier, we said that we considered agricultural systems as energy transformation systems, so we used the EROI (Energy Return on Energy Input), which is the ratio of the energy obtained over the energy spent to get an energy source (Hall et al. 1986). Sometime later, these same authors found that the non-equivalence of EROI values, even when calculated for the same process, was one of the common problems when comparing energy efficiencies. As they say, the concept is simple "but the evil is in the details" (Murphy and Hall 2010). When to stop accounting for the energy costs and how to take into account the embodied energy are the two main 'evil' source of differences among results (Mulder and Hagens 2008). Hence, we agreed that in order to go for more historical case studies to answer the above questions, we needed to review the methodology followed in Cussó, Garrabou, Olarieta, et al., (2006).

Calculating energy efficiency requires first, translating into energy units the biomass produced within the agroecosystem. Some of this biomass is not harvested (e.g. weeds, leaves, branches, etc.) we called it Unharvested Biomass. Some part of the biomass harvested goes outside of the system and others are harvested but remain inside the system (e.g. as feed for livestock or giving consistence to manure piles), we called it Biomass Reused. We called Final Produce the part of the harvest that goes outside the system, together with the extractions of accumulated wood or livestock products (Barnyard Products in our scheme). We called Net Primary Production (NPP) all the solar energy transformed to plant biomass in a year, so it is the sum of Land Produce and Unharvested Biomass. Everything is detailed in the previous chapters.

Second, it requires classifying the energy flows into inputs and outputs. Calculating efficiencies—in our case EROI—has meaning with linear processes, but the energy flows in an agroecosystem are essentially cyclical, and so the beginning and the end are purely defined by the observer. Our challenge was to adapt the most common concept of EROI used in agricultural systems to the very cyclical nature of agroecosystem because otherwise the diminishing energy returns of agriculture when changed towards the industrial mode we describe, is lacking analytical potential.

Then, we decided to distinguish between external and internal inputs. We made the differentiation on the input side and not on the outputs because, as explained in section 1.2, different types of agriculture use different types of energy inputs, which have different implications on landscape configurations. So under this scope the flows of Biomass Reused and Unharvested Biomass could be seen as an investment in the complexity of landscape and hence in biodiversity. On the other hand, this could be seen at the same time as a cost—a Final Produce opportunity cost—as past organic agricultures and the ones using Low Energy Inputs (LEIT) rely more on ecosystem services than industrial ones. For example, the maintaining of these flows (Biomass Reused and Unharvested Biomass) is far from optional when using auxiliary fauna for pest control (Gliessman 1998; Altieri and Nicholls 2004; Tscharntke et al. 2005; Bianchi et al. 2006). By contrast, industrial agriculture substituted them with pesticides.

Hence, these flows could be seen at the same time as an investment or as a cost, it is not for nothing that when comparing organic agricultures with industrial agriculture Guzmán and González de Molina (2009) have coined the concept 'land cost of sustainability'. Whereas both arguments are equally logical, I took inputs as an investment. As recalling our hypothesis, landscape heterogeneity is a result of internal inputs (in our case Unharvested Biomass and Biomass Reused) whose quantity and quality carry the information that is reflected through landscape configurations. In this way, when the output is the Final Produce, the denominator of the efficiency ratio or the Total Inputs Consumed (TIC) is a sum of the External Inputs (EI) and the internal inputs harvested, which is the part of the harvest that remains in the system as Biomass Reused (BR).

Agroecosystems are designed by information flows of humans e.g. know-how, rules and norms, worldviews, etc., this intangible part of societies (González de

Molina and Toledo 2011) co-evolves with the ecosystem and is thus reflected in different landscapes.

Ecosystems without human intervention change along time with the process of ecological succession and, as Margalef stated, not only the living biomass but other structures like the dead trunk of a tree or the carbonate structures of corals, which are no longer alive, carry information and give complexity to the system (Margalef 1997). These dissipative structures carry the information that orders the system and organise it with more or less complexity (Prigogine and Stengers 1984). Hence the process of succession towards complexity is explained by the relation of the energy flows and the standing biomass in the broad sense, including dead biomass or exosomatical artifacts such as coral reefs (Margalef 1997).

When humans interact with an ecosystem, the diversity drops and this ratio of primary production to biomass increases, even if humans introduce manure, other fertilisers or other inputs, there is a simplification of the structure of the ecosystem with the destruction of many homeostatic mechanisms (Margalef 1968). Agroecosystems are then a simplification of ecosystems, but still there are significant differences among them depending on the kind of agricultural practices. Coherently, from an agroecological point of view, Gliessman (1998) defined the Productivity Index as the relationship between the total biomass accumulated in the systems and the Net Primary Productivity (NPP), and not only to the biomass harvested or the yield of a single species. The higher the non-harvested biomass, the higher the Productivity Index because "Ultimately it is this biomass that supports the process of sustainable production. In a sustainable agroecosystem, therefore, the goal is to optimize the process of productivity so as to ensure the highest yield possible without causing environmental degradation, rather than to strive for maximum yields at all costs." (Gliessman 1998).

At the local scale, this applies to unharvested biomass such as weeds and crop residues recycled. Indeed, crop residues left on land improve agricultural productivity by protecting soil from erosion, water runoff, supplying organic matter and nutrients and benefit species diversity (Pimentel et al. 1992). At landscape scale, this applies to edge habitats and patches of non-cultivated land.

Up to this point, it is clear that to analyse the performance of an agroecosystem the biomass appropriated by humans is as important as the biomass 'left' within the agrecoystem. This has two main implications for our energy analysis: first, to compare the energy performance of agroecosystems we need information about the internal and external inputs, and second, we need information about the biomass accumulated in the system.

On one hand, we made three ratios depending on whether the inputs considered were from outside the system —External Inputs—, from harvest—Biomass Reused—or both—Total Inputs Consumed.

As they share terms, they could be related, and so placed in a graphic with all the EROI values mathematically possible. This would allow us to compare the energy performance of different, past and present systems. According to the graphic, the higher the internal and external efficiencies, the higher the overall efficiency, which will be more affected by marginal increases of one or another depending on the location of the system analysed. Beyond these terms, what would the desired energy efficiency of an agricultural system be? As a matter of example, Hall et al., (2009) dared with a minimum EROI of 3:1, and early in the nineteenth century (Podolinsky 2004) bet for 10:1, however I think that having a minimum EROI universal reference is worthless due to three main reasons. First, as we said before, the details are so evil that it makes nonsense to use a benchmark whose details are unknown. Second, as agroecosystems are complex systems, "good scoring" in one indicator does not mean an overall desirability or sustainability. It makes more sense to analyse a group of case studies and try to find which factors share the ones located in nearby areas of the graphic. Third, using just the graphic, we lack information about the already mentioned accumulated biomass—Unused Biomass—e.g. weeds, from hedgerows, fallows or non-cropland area.

On the other hand, like the other side of the coin, we proposed to calculate the return of energy available to sustain humans as well as the rest of heterotrophic species—NPPEROI (Table 3.2). Indeed, to know the energy invested to produce energy flows for other species we have to test the human appropriated flows, i.e. the Final Produce, that includes the Land Produce going outside the system and the Barnyard Produce, e.g. meat—NPPEROI-FEROI (Eq. 3.1). This is coherent with what we said in section 1.2 about the relationship between low intensive agriculture and a landscape mosaic combining non-crop lands, both combined provide a certain level of disturbance and biomass in the system supporting a certain level of biodiversity.

$$NPPEROI - Final\ EROI = \frac{UB + BR}{TIC} - \frac{BP}{TIC} \quad \text{Eq. (3.1)}$$

Summing up, there were two main contributions from the previous two chapters. First, we found a way to compare the energy efficiency of different flows in different systems by relating the internal and the external efficiencies to the overall efficiency. Second, to relate the energy of diminishing returns of agriculture and landscape heterogeneity and biodiversity, we reversed the concept of EROIs proposed by thinking on the efficiency of the energy invested by humans to produce flows available for non-human species as expressed in Eq. 3.1. This is the same as saying that landscape heterogeneity and species biodiversity rely both on unharvested and internal biomass used in farm systems. In the last two chapters, we adapted the energy analysis to History and left the door open to the necessary relation of past agricultural systems with Agroecology.

3. The Socio-Ecological Transition c.1860-1999

The changes that occurred in the five Catalan villages between c.1860 and 1999 do not differ from other places in the Western Mediterranean. While population densities quadrupled, livestock densities per cropland area increased 37 times (Table 3.1). This would not have been possible without a fossil-fuelled leap over the food/feed competition in limited cropland. In Catalonia c.1860 vineyards were a way to complement the supply of firewood and feed that the uncultivated land covers were barely providing (Tello et al. 2012). The vineyard land almost disappeared from the area in 1999 (Cussó et al. 2006a) together with the decrease of firewood needed due to the use of gas in domestic kitchens.

Table 3.1. Main characteristics of the five municipalities of Caldes de Montbui, Castellar del Vallès, Palau-solità i Plegamans, Polinyà and Sentmenat c.1860 and in 1999.

	c.1860	1999
Annual rainfall (mm)	640	
Population density (inhab/km^2)	71	279
Cropland density (ha/cap)	0.64	0.10
% forest, scrubland and pastures over total area	52.2	58.9
Ratio forest, scrubland and pastures over annual crops[2]	2.9	2.3
Ratio permanent land covers over annual crops	4.6	2.4
Livestock density per cropland area (LU 500 kg/km^2)	17	636

Source: Cussó, Garrabou, Olarieta, et al., (2006a).

The comparison between the lists of indicators calculated (Table 3.2) shows the paradigmatic trend that agricultural systems followed once they ended the Socio-Ecological Transition to an industrial regime or mode of appropriation. The energy efficiency, either considering only external inputs or the total inputs consumed, decreased. On the contrary, the harvested biomass reinvested in the

[2]Although questionable, we refer to *herbaceous crops* and *annual crops* indistinctly when we want to group all the crops that are not wooden and perennial.

system decreased (due to e.g. lower straw/grain ratio, less cropland devoted to feed, etc.) and the harvest increased, hence the efficiency of the use of the crop residues has increased.

The difference between NPPEROI and Final EROI—recall that we defined it as an indicator for the room left for species other than humans—decreased significantly in 1999 despite the fact that the area covered by forest, scrubland and pastures increased. More specifically, the area of forest increased while the area known as *erial*, i.e. pastures and scrubland altogether, decreased.

Table 3.2. List of EROIs obtained in the five Catalan municipalities c.1860 and in 1999.

	c.1860	1999
Final EROI (FEROI = FP/TIC)	1.05	0.21
External Final EROI (EFEROI = FP/EI)	10.49	0.23
Internal Final EROI (IFEROI = FP/(BR+W))	1.17	2.18
NPP EROI (NPP /TIC)	3.18	0.41
NPP EROI - Final EROI = (UB+BR-BP)/TIC	2.12	0.20

FP: Final produce; TIC: Total Inputs Consumed; EI: External Inputs; BR: Biomass Reused; W: Waste; NPP:Net Primary Production; UB: Unharvested Biomass). Source: our own in Marco et al.(n.d.), recalculated from Cussó, Garrabou, Olarieta, et al. (2006).

Industrial agriculture relies on external inputs coming from fossil fuels in search of greater labour and land productivity, it also tends to engage in monocultures and reduce internal reuses. Not only techniques, but the selection of cultivars followed this trend as was the case in the last decades of the twentieth century in Spain, when the wheat to grain/straw ratio decreased due to the use of dwarf cultivars, although the straw per unit of area increased slightly due to the higher number of stems per plant (Pujol-Andreu 2011). Compared to pre-industrial agriculture, this entailed a reduction in agroecosystem complexity as expressed in the loss of landscape heterogeneity, with the ensuing biodiversity loss and the regulatory services provided overall since 1950s (Tello and Marull 2006; Marull et al. 2008a; Marull et al. 2010). This in turn required replacing them by other artificial controls, such as pesticides and mechanical work, increasing again the amount of external inputs. This feedback is represented in the energy profile by a decrease in EFEROI, EFEROI and NPPEROI - Final EROI and in an increase of IFEROI.

In order to compare the relation between Final EROI, Final External EROI and Final Internal EROI among the different systems we drew the graphic that represents all the possible cases and we placed our case study c.1860 and 1999 (Figure 3.2). Increasing Final EROI always depends on the efficiency of the management of external inputs (EI) and internal inputs (BR). In our case c.1860 this would have involved increasing the Final Produce and decreasing the Biomass Reused and therefore would give a certain margin to increase the external inputs.

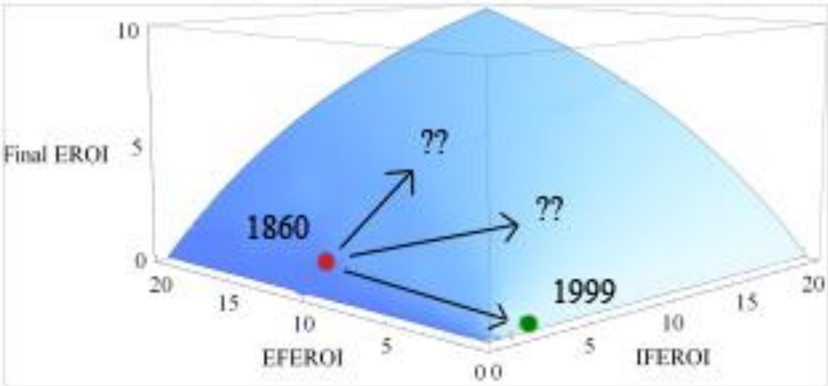
The limitations of cavorting with the indicators of our energy analysis, is that we cannot explain only in energy terms new sustainability problems beyond the energy analysis: such as less land available for food production, the expelling of labourers from land—as some land uses admitted more people than others (Badia-Miró and Tello 2014)—or decreasing fertility.

In addition, our model does not predict the interaction among components e.g. we cannot predict how a decrease of Biomass Reused would affect Final Produce, or how an increase of Biomass Reused would affect Human Labour. However, we can speculate with agricultural practices that were used c.1860 to increase fertility to see to what extent was possible a better management of the Biomass Reused.

As we will see in the next chapter, Spanish agronomists at the beginning of the twentieth century complained about the bad management of manure and other fertilising material, which involved the loss of most nitrogen (Cascón, 1918; JCA, 1921). Improving infrastructures to protect manure heaps of rain and excessive loss of moisture using available technology (De la Cruz-Lazaparán 1924) or using the straws as beds instead of leaving them in fields (Cascón 1918) would have increased fertility and hence potential harvests without increasing the use of internal biomass. That would have been at the expense of increasing external inputs in the form of human labour.

The same would have happened by sowing fallow land with green manure or increasing the use of human excrements and other organic waste from households. The increase of population densities and the deficient sewage systems in Catalonia at the beginning of the twentieth century (García-Faria 1893) made some practices tedious and unsafe. Instead of just eliminating this source of fertiliser, some of the agronomists of the time recommended mechanisation of the collection, such as theuse of pumps to empty deep cesspits. As De la Cruz-Lazaparán (1924) observed, although it was cheaper, forcing labourers to do it by hand was a "misunderstood economy".

Figure 3.2. Plotting the Internal and External final energy returns behind the Final EROI attained by the farm system of the Catalan study area



Note : c.1860 is in red and 1999 is in green. The arrows illustrate some of the possible trajectories resulting from the modification of EFEROI or IFEROI. Source: chapter 2.

Constraints for the improvement of fertility were not only at the cost of human labour. Other social factors could have been very important: land ownership—as investing in fertility is a long-run investment—, bargaining power to decide which tasks should be implemented, technology to complement or make more efficient human labour, conflict—the Catalan countryside, overall vineyard areas, became highly conflictive at the beginning of the twentieth century (Giralt 1965; Balcells 1968; Hansen 1969; Carmona and Simpson 2009; Colomé 2014)—and even the reluctance of farmers to change practices and the influence of social pressure and individual behaviour on it.

Climate is a constraint too as some leguminous crops such as clover used successfully in other places as green manure are vulnerable to drought as use to happen in Mediterranean summers (FAO 2012). However, the use of green manures—with other species such as sainfoin that are more drought-resistant (FAO 2012)—is difficult to track with our sources since they do not grain and are not included in harvest reports.

Moving towards other energy profiles would involve changing the underlying sets of linkages between agroecological functioning and socioeconomic drivers. This is the limit of our own proposal too since it is not prepared to model reciprocal changes between interwoven flows in other dimensions than energy. Indeed, efficiency on energy use in agroecosystems is a necessary indicator but at the same time it is just one among others used in the assessment of farming performance (Gliessman 1998; Gomiero et al. 2008; Funes-Monzote et al. 2009).

4. Final remarks

At the beginning of this chapter, we asked ourselves if the decrease in the energy efficiency of the system was the only possible pathway followed for the agrarian systems studied. By disaggregating between internal and external components of energy efficiency, we put forward the importance of the internal recycling of biomass that is a component of the production process not considered in conventional Agricultural History. The main difficulty to build the energy profile of a historical agroecosystem is to find data. Some qualitative data is available, such as the opinions of the agronomists mentioned before, while the main available quantitative data are population census, manorial inventories, church tithes, parish and notary registers and cadastral sources. The graphic shown in Figure 3.2 is a way to relate the internal and the external efficiencies with the overall efficiency, and provides a basis for comparison of more areas and dates.

Notwithstanding, to build our model we set aside two big discussions. On one hand, there is the relation between the terms of the efficiencies, which is of a complex nature. For instance, we do not know to what extent a decrease in the Biomass Reused would affect the Final Produce of the External Inputs. The implication of our assumption is that our model cannot predict the behaviour of the system when changing one of the terms; it is limited to describe the place in the graphic whenever all terms are known.

On the other hand, we packed under the label 'External Inputs' a mixture that provoked controversy even among ourselves, as it mixed either non-equivalent energy units (Giampietro and Sorman 2012) and renewable and non-renewable energy sources, which is at the core of changes throughout the SocioEcological transition of agricultural systems (Campos and Naredo 1980; Guzmán and González de Molina 2006). This limits our proposal as comparison, as the interpretation *per se* of the ratios obtained is ambiguous. However, we do not see a way to link the diminishing energy returns of industrial agriculture throughout history with its related landscape dimension without taking this liberty.

One of our initial aims was to relate the diminishing returns of industrial agriculture with loss of landscape heterogeneity and biodiversity loss. As within this work we only had space to analyse two cases, we ended with two hypotheses. The first hypothesis was that the existence of a significant proportion of biomass reused is a hallmark of an integrated land-use management that tends to increase the complexity and the number of habitats in an agroecosystem. The second hypothesis was that the difference between NPP EROI and Final EROI could control whether a change in the energy throughput undermines or not the biomass available for other species. As we saw in section 1.2, it was not only non-cropland areas but also some of the low-intensity areas generated by traditional agricultures—the same areas that, at least in the Mediterranean, were and are being abandoned. While the relation between landscape heterogeneity—always with enough patch-size—and the flows of Biomass Reused and Unharvested Biomass seems to be clearly positive, what is the relationship with the energy efficiency of the agricultural system?

At this point, it is interesting to recall the idea from Ulanowicz and Ho (2005) that all living systems are always organized in nested space-time physical structures cycling energy flows. Differing from the concept of Prigogine and Stengers (1984), they distinguish between dissipative flows and non-dissipative cyclic flows of energy i.e., energy embodied in stored biomass (Ho and Ulanowicz 2005). Due to coupled activities between all structures, energy transfers occur and some structures can present local near-equilibrium states while the entire organism is far from thermodynamic equilibrium (in the classical sense). Then, for a given energy input, the higher the number of cycles the higher the complexity of the system, as wastes from one structure will be resources for the other, hence, non-dissipative flows of energy will prevail over dissipative at global system's level. The opposite would happen with the almost-linear system of industrial agriculture (Ho 2013).

This idea of different local efficiencies and nested efficiencies related with the internal flows in the agroecosystem—Unharvested Biomass and Biomass Reused in our case—can be related with landscape analysis across scales. A way to do it could be trough the concept of landscape efficiency, which has been defined as those forms of economic land-use that meet human needs while enhancing ecological complexity and function (Marull et al. 2010). The authors of that study used two indexes, the Landscape Metrics Index and the Ecological Connectivity Index to study the loss of landscape efficiency in our same area of study and found it coinciding with the energy efficiency loss from Cussó, Garrabou and Tello(2006b). Our definition of interrelated energy ratios could help to create a model mixing the indexes across scales in a land matrix in further studies.

The development of the work in the last two chapters was strongly influenced by the first steps made in (Cussó et al. 2006a; Cussó et al. 2006b), in these studies we started by calculating energy efficiencies. As we said before, energy efficiency is used as an indicator in the assessment of the performance of farming systems, but only among other sets of indicators (Gliessman 1998; Gomiero et al. 2008; Funes-Monzote et al. 2009). During the Socio-Ecological Transition of agriculture, the increasing opportunity costs of human labour and capital at farm system level brought on by economic development pushed for the abandoning of traditional farming strategies, thus going against the recycling practices and favouring the linearisation of the pattern of flows (Giampietro 1997a).

Hence, to answer the question of the implications of the social and economic feasibility of higher energy efficiency in agricultural systems, there is need of a study of systems in the hierarchy, more scales and the external and internal constraints together with a number of inconvenient questions (Sorman and Giampietro 2013). In fact, for instance, in a model built by De Aranzabal et al. (2008) for Mediterranean areas, more complex combinations of cropland, pastureland, forest and scrubland than current ones were correlated with less investment in industry and tourism sectors, less higher education, increase of rural population and changes in the livestock type compositions by increasing sheep and to a lesser extent cows among others[3]. Then, the next step after having more case studies could be to relate these factors with energy efficiencies and its ensuing correlation within a complex landscape.

In addition, we have seen that techniques of better fertility management could have increased the energy efficiency without involving drastic social changes. This brings us to another question: had the Mediterranean past-organic agricultures available means to increase fertility? What were the main constraints? The aims of the next chapters go towards these questions.

[3]Whereas this is the only study that we found for SpanishMediterranean areas, we think that these factors could be redefined by using an agroecological perspective. Current diverse agricultural land immersed in a matrix of forests are related withagroecology-based peasant food systems, whose common features are well-known and described elsewhere, for example in Altieri and Toledo(2011).

Bloc 2. Nutrients flows

Chapter 4. Fertilising methods and nutrient balance at the end of traditional organic agriculture in the Mediterranean bioregion: Catalonia (Spain) in the 1860s[1]

1. Introduction

This work is part of a larger project that seeks to clarify the reasons that led to traditional organic management in the Mediterranean agricultures being abandoned. Seen from the standpoint of nutrients replenishment into the soil, how sustainable had they been? Was there still room to improve on organic procedures in a region like Catalonia (Spain)? After having reconstructed the energy balance in the same area around 1860 –where a positive energy return on energy investment of around 1.41 or 1.67 depending on the boundaries of the area under study was found (Cussó et al. 2006a; Tello and Marull 2006; Cussó et al. 2006b; Tello et al. 2008b)—, we intend to complete this socio-metabolic approach by estimating the nutrient balance and assessing the maintenance of soil fertility.

2. Agroecological and socioeconomic features of the area under study

Our case study is the municipality of Sentmenat located in the Catalan Vallès county, some 35 km north-east of Barcelona, with a total extension of 2,750 hectares, of which 59% were cultivated in 1861.

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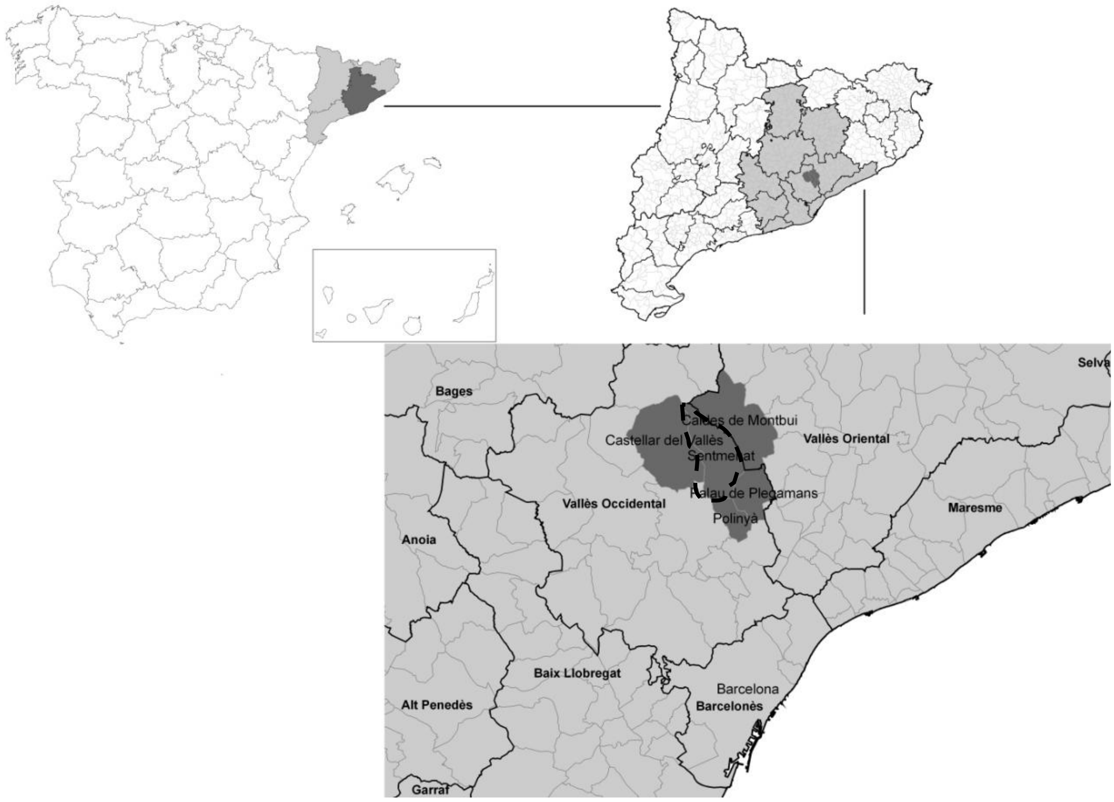
[1] This chapter is a version of a paper previously published in Human Ecology as Tello, E., Garrabou, R., Cussó, X., Olarieta, J.R., Galán, E., 2012. Fertilising Methods and Nutrient Balance at the End of Traditional Organic Agriculture in the Mediterranean Bioregion: Catalonia (Spain) in the 1860s. Hum. Ecol. 40, 369–383. doi:10.1007/s10745-012-9485-4. It is coauthored with Enric Tello, Ramon Garrabou, Xavier Cussó and José Ramón Olarieta. My contribution was the correction of the calculations, making of figures and reestructuration of the final writing of the paper.

Figure 4.1.Location of the study area: the municipality of Sentmenat and neighbouring townships in the province of Barcelona and Catalonia (Spain)



In the lower right map dashed lines delimit the municipality of Sentmenat, gray lines delimit the municipal boundaries, and black lines the county borders.Source: our own.

The village was set up during the tenth century AD in a small plain located in a tectonic basin between Catalonia’s littoral and pre-littoral mountain ranges. It has an average slope of 9.7% and an annual rainfall of 643 mm. The heliothermic Huglin index of 2,168 is good enough for winegrowing—it has a minimum requirement of 1,500 and reaches a maximum municipal score of 2,778 in Catalonia (Badia-Miró et al. 2010). Rainfall and temperature allow for reasonable yields in cereal crops, at least in flatlands with a higher water retention capacity.

In 1860 there were 354 families and 1,713 people were registered in Sentmenat, giving a population density of 59 inhabitants per square km. This meant that 1.7 hectares of municipal area or 1.4 of cropland were available per inhabitant. 70% of the labour capacity was devoted to agriculture and 21% to industrious activities. As many as 208 out of the 241 agricultural families were “peasants” or “landowners”, while 21 of them worked as ploughmen tenants and 12 as daily labourers. Moreover, 187 out of the 208 landowners were autonomous peasants that toiled their land mainly with the family workforce, only hiring someone from the labouring families in peak seasonal times. Many landless labourers had kinship ties with peasant owners (Garrabou et al. 2010). Despite being far from egalitarian, this rural society enjoyed a high degree of access to the land and can be basically seen as a peasant community (Netting 1993; van der Ploeg 2008).

The inequality Gini coefficient was 0.58 for the distribution of total land ownedin 1859, or 0.51 if only cropland is taken into account. In 1735 they had been 0.77 and 0.67, and rose again to 0.76 or 0.70 in 1918following the Phylloxera plague that killed all the old vines in the 1880s (Badia-Miró et al. 2010). The reduction in landownership inequality between 1735 and 1859 had been driven by vineyard specialization (Garrabou et al. 2009). Many landowners and some peasant owners leased poor sloping soils previously covered by scrub and pasturelandto an increasing number of non-heir relatives or landless immigrants who built terraces and planted vineyards (Olarieta et al. 2008). A Catalan sharecropping contract called *rabassa morta* was used, which lasted until the death of the vines planted. This explains the lower inequality recorded, which was mainly a reduction in land-access and income inequality rather than in landownership distribution as such (Tello and Badia-Miró 2011).

3. Land-uses, livestock densities and manure

Vineyard specialization was developed during the nineteenth century keeping some amount of land, usually the best of it, devoted to grain, legumes and vegetables in a poly-cultural landscape. With only 12.4% of the land in 1861, natural pastures were extremely scarce and very poor to raise livestock. A great deal of cropland consisted of vineyards or olive groves that extracted less N, and supplied the by-product of pruning. Thanks to the increase of arboriculture, the ratio between uncultivated area and land sown with herbaceous crops could be kept up to 2.4 in 1861, and the ratio between permanent land-covers and annually sown-land up to 5.1 (Table 4.1). All these features were typical of a Mediterranean-type of intensive organic agriculture (Sieferle 2001; Wrigley 2004), which plunged into a crisis during the economic globalization experienced at the end of the nineteenth century up to the twentieth (Tello and Marull 2006; Marull et al. 2008a; Tello et al. 2008b).

Table 4.1. Cropland and other land uses in Sentmenat in 1861

	ha	% of cropland	% of total area
Vegetal gardens and irrigated herbaceous crops	67.8	4.2	2.5
Rain-fed herbaceous crops	365.5	22.6	13.3
Vineyards	1,066.1	65.9	38.8
Olive groves	113.1	7.0	4.1
Other rain-fed woody crops	5.2	0.3	0.2
Total cropland	1,617.7	100.0	58.8
Woodland and scrub	698.4	--	25.4
Pasture	341.4	--	12.4
Unproductive or developed	92.5	--	3.4
TOTAL AREA	2,750	--	100.0
ratio between woodland, scrub and pasture/cropland			0.64
ratio between woodland or scrub/cropland			0.43
ratio between woodland, scrub and pasture/herbaceous crops and vegetable gardens			2.40
ratio between woodland or scrub/herbaceous crops and vegetable gardens			1.61
ratio between woodland, scrub, pasture, vineyards ,olive groves, and other woody crops/herbaceous crops and vegetable gardens			5.13
ratio between woodland, scrub, pasture, vineyards, olive groves and other woody crops/cropland			1.37

Source: our own from cadastral records in the Archive of the Crown of Aragon (Barcelona).

A crucial factor of these pre-industrial organic agricultures was the number of cattle fed on uncultivated land and cropping forages, in order to provide enough manure to the land sown with cereals (Krausmann 2004). In Sentmenat there were only 5 head per square km in 1865, or 7 if donkeys were included (Table 4.2):

Table 4.2. Livestock and manure in Sentmenat in 1865

Manure produced	heads	per head kg a day	total kg a year	total available[a]
Horses	5	22	40,150	40,150
Mules	103	22	827,090	827,090
Donkeys	76	8	221,920	221,920
Cows and oxen	26	34.15	324,060	324,084
Sheep	225	2.3	188,888	94,444
Goats	70	2.3	58,765	29,383
Pigs	310	6.5	735,475	735,475
Chickens and rabbits[b]	1,735	0.137	86,759	86,759
Transhumant sheep	350	1.15	146,913	73,456
TOTAL (weight of fresh manure)			2,630,042	2,432,760
%N-P-K losses from fresh to composted manure[c]		50% N	3% P	20% K
N-P-K contained in composted manure[d]		8,515 kg N	3,776 kg P	8,563 kg K
Livestock Units of 500 kg (LU500)	199.3	t cropland ha^{-1}		1.50
LU500 square km^{-1}	7.25	t sown-land[e] ha^{-1}		5.61
LU500 cropland ha^{-1}	0.12			
LU500 sown-land[e] ha^{-1}	0.46			

[a]For sheep and goats maintained in grasslands 50% of manure has been discounted considering that it could not be recovered by locking the herd at night in a pen or taking it to stall. [b]Estimated by us from the available feed and assuming the existence of five chickens or rabbits per household. [c] [d]See Table 4.7. [e] Rain-fed and irrigated herbaceous crops and vegetable gardens.Source: our own estimate made from the livestock census of 1865 in the district, the data provided by contemporary literature and the assumptions made in the energy balance published by Cussó, Garrabou, Olarieta and Tello (2006a). The following references have also been taken into account: Bouldin et al. (1984), Loomis et al. (2011), Sørensen et al. (1994), Tisdale and Nelson (1956).

That meant a live weight density of only 12 LU500 per cropland square km. In comparison, Fridolin Krausmann has found in the intensively cropped Austrian village of Theyern 24 LU500 per square kmof agricultural areain 1829, while in the very extensive land-use of the American Great Plains Geoff Cunfer has accounted a range from 4 to 13 LU500 in Finley Township (Kansas) during the years 1895 to 1915 (Cunfer and Krausmann 2009). This livestock density was clearly inadequate for a highly intensive organic agriculture and could only provide 1.5 tonnes of fresh manure per cropland hectare, a figure which coincides with the 1.37 tonnes accounted for in the first statistical survey on fertilisers carried out in 1919 in the province of Barcelona—while the dose recommended by agronomists was 10 tonnes per cropland hectare (Aguilera 1906; Cascón 1918; Slicher van Bath 1963).

Nevertheless, these average figures also conceal marked differences between crops. No manure was used for growing vines, and only very small quantities in olive groves. This explains the role played by vineyard specialization in reducing the ratio between land sown with cereals and uncultivated land (Table 1.1). If we assume that all manure was applied for growing grains, livestock densities would raise to 46 LU500 per square km of croplandand average doses to 5.6 tonnes of fresh manure per sown-land hectare, which also coincides with the 6 or 7 tonnes per hectare attributed by other sources to the rain-fed cultivation of cereals in the province of Barcelona during the second half of the 19th century—including doses from 22 to 32 tonnes per hectareapplied in irrigated lands. These would have doubled the doses applied in the United States, that amounted between 2.5 and 5 tonnes per hectare at the time (Burke et al. 2002; Cunfer 2004; Cunfer 2005), and matched the average figures in England and Wales that ranged from 4 to 5 tonnes per hectarefrom the mid-nineteenth century to the WWI (Brassley 2000).

4. How the nutrients gap was closed

Assuming that woody crops received no manure there remains a significant gap between the available livestock densities and the fertilisation required. Hence we have come to the conclusion that either some other organic fertilisers were able to fill this gap, or an unsustainable soil mining was at stake until chemicals came along. By comparing fertilising practices in Kansas and Austria, Geoff Cunfer and Fridolin Krausmann conclude that thanks to their high livestock densities Austrian farmers were able to return over 90% of N extracted to cropland, although they produced little marketable crop surplus. The farmers who colonized the Great Plains produced plenty of exports but used few animals to exploit rich grassland soils, thus returning less than half of the N extracted. After depleting soil fertility for over six decades, they faced a decline in crop yields from 1880 to 1940 until chemical fertilisers arrived (Cunfer and Krausmann 2009). Between these two examples, where can the path followed by Western Mediterranean agriculture be placed?

We try to find an answer to this question by reconstructing a complete nutrient balance in our case study. Nutrient outputs and inputs in crops and seeds have been estimated from its content, taking into account harvest index and the reuse of by-products. Table 4.3 shows the amount of N-P-K taken up by different crops, without having discounted seeds and distinguishing between main consumed products and reused by-products. Some 40 kg N per hectare were annually removed in irrigated lands and vegetable gardens, three times more than the average and 5.6 times the N taken up by vineyards. Rain-fed intensive rotations of grains sown without fallow extracted 39% of all N in 22.6% of cropland, about 22 kg N per hectare. Vineyards drew 7 kg N per hectare, including grapes and pruning-shoots. In spite of covering two thirds of cropland they only took 38% of N, 28% of P and 18% of K.

Table 4.3. Estimates of nutrients removed by crops in Sentmenat around 1861-1865

4.3.1. Main product for human consumption or animal feed				
	net fresh weight kg	kg N a year	kg P a year	kg K a year
Irrigated wheat	19,166	353	63	67
Irrigated corn	17,856	276	49	67
Hemp	15,561	230	36	72
Beans	18,323	651	86	315
Rain-fed wheat	87,496	1,879	337	357
Rain-fed corn	29,884	541	97	103
Mixture of rye and other cereals	15,052	241	43	59
Barley	26,513	459	188	125
Forages	174,903	1,235	268	752
Peas	41,155	1,070	96	254
Olive oil from olive groves	16,104	0	0	0
Grape juice from vineyards	2,070,079	0	414	2,070
Vegetables in orchards and gardens	171,618	422	211	492
Fresh fruits in orchards	27,878	8	5	23
Nuts in orchards	6,638	11	5	16
NET TOTAL HARVEST	2,652,609	7,376	1,898	4,772
4.3.2. Crop by-products and residues				
	fresh weight kg	kg N a year	kg P a year	Kg K a year
Straw & stubble of irrigated wheat	45,699	243	155	226
Straw & stubble irrigated corn	9,723	50	37	152
Residues & stubble of hemp	11,413	55	43	183
Straw & stubble of beans	13,111	178	51	151
Straw & stubble of rain-fed wheat	194,029	1,063	658	955
Straw & stubble of rain-fed corn	57,536	47	30	122
Id. mixture of rye and other cereals	48,505	158	100	147
Straw & stubble of barley	91,696	440	174	275
Straw & stubble of forages	69,621	518	115	323
Straw & stubble of peas	21,422	257	91	442
Pruning from olive Groves	309,950	1,937	542	2,015
Pruning from vineyards[2]	2,733,716	7,574	1,981	4,303
By-products & residues of gardens	66,289	287	93	264
TOTAL BY-PRODUCTS	3,672,710	12,807	4,070	9,558

[2]This include together leaves «*pàmpols*», pomaces and wodden parts cut from winter and spring prunings.

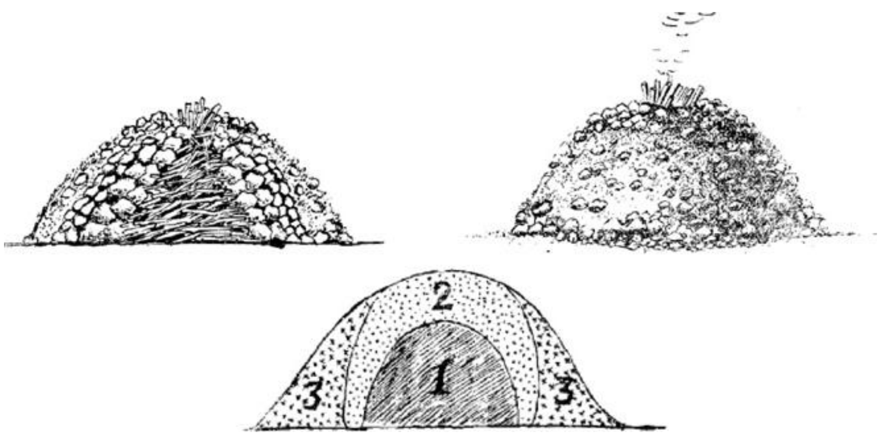
4.3.3. Distribution of nutrients removal between the main agro-ecological flows

	kg N a year	%	kg P a year	%	kg K a year	%
Vegetable garden products	654	3.2	286	4.8	686	4.8
Cereals and legumes for food[ab]	5,414	26.8	1,621	27.1	2,612	18.2
Feed and fodder for livestock[b]	4,529	22.4	1,098	18.4	2,534	17.7
Vineyards	7,574	37.5	2,395	40.1	6,373	44.5
Olive groves	2,011	10.0	570	9.5	2,123	14.8
TOTAL REMOVED BY CROPS	20,182	100.0	5,970	100.0	14,328	100.0
Losses by natural processes	9,049	--	0	--	2,051	--
NUTRIENTS REMOVED	29,231		5,970		16,379	

[a] Hemp included; [b] Either rain-fed or irrigated. Source: our own from Cussó, Garrabou, Olarieta, et al. (2006a), and taking into account, among others, Angás et al. (2006), Loomis et al. (2011), and Tisdale and Nelson (1956).

Overall, this distribution reveals the rationale behind the priority given to the scarce manure: it was first applied to irrigated land, and then to rain-fed cereals rotated with N-fixing leguminous crops or green manures. Vineyards were not manured except when planting, and only received small amounts of other organic fertilisers like leaf litter and branches buried in ditches dug between rows of vines, or burning and ploughing into the soil the so-called *hormigueros* (or *formiguers* in Catalan). These were similar to small charcoal-kilns made up with piles of dried vegetation that were burnt under a soil cover, as to generate a slow and incomplete combustion. The material obtained was used as fertiliser or soil conditioner (Olarieta et al. (2011),and Figure 4.2).

Figure 4.2. Preparation and composition of a fertilising *hormiguero*



1: scorched earth; 2: soil heated between 100 ◦C and 200 ◦C, the most fertile obtained in the *hormiguero*; 3: soil barely heated.Source: reproduced from Mestre and Mestres (1949) in Olarieta et al. (2011).

In the 1,618 hectares ploughed in Sentmenat circa 1860-65 some 20,195 kg of N were annually removed, 12.5 kg N per hectare. All animal manure locally produced only contained about 12,164 kg N. Considering that at least 50% was lost in the dung pile, the N available would be reduced to 6,082 kg, or a maximum of 3.8 kg N per hectare a year (Cascón 1918; Tisdale and Nelson 1956; Johnston 1991). Owing to this deficiency in N supply from manure other sources of nutrients and agricultural fertilisation practices were sought in order to fill this gap. Five different possibilities are considered: 1) human sewage and garbage; 2) symbiotic bacterial fixation through leguminous crops; 3) green manures; 4) burying fresh biomass into the soil; and 5) ashes, charcoal and reheated land burnt in piles of *hormigueros*. In order to assess the role played by each of these contributions a full nutrient balance is needed.

One of the most difficult components of any organic nutrient balance is the value adopted for atmospheric N fixation made by symbiotic bacteria. Even today, scientific literature presents a bewildering variation in the figures of N fixed by leguminous plants. This can be largely explained by the circumstantial nature of the symbiosis between legumes and Rhizobium bacteria, which entails that the presence of high doses of mineral N in the soil suppresses bacterial fixation. Moreover, only a part of the N content of a leguminous plant comes from the atmosphere. Before the Rhizobium nodulation develops in the roots, the plant needs to uptake mineral N from the soil and therefore not all the N absorbed before the flowering and maturation of the grain can be attributed to the Rhizobium nodules. The lower energy cost of drifting carbon for their own growth, rather than to Rhizobium colonies that may remain inactive, explains why legumes break symbiotic N fixation when there is enough mineral N in the soil.

This flexibility has a lot to do with the crucial role legumes played in the millennial development of organic agricultures, in which mineral N was practically always lacking in the soil (McNeill and Winiwarter 2006). Unfortunately, this creates a considerable uncertainty about the actual symbiotic fixation in each particular circumstance. Values ranging from 10 to over 300 kg N per hectare a yearhave been estimated. There are examples and opinions that reduce N symbiotic fixation to very small values, or even assume a net negative outcome if the grain is removed and plant residues are not incorporated into the soil. The only safe rule is that symbiotic and free fixation would be greater the poorer the mineral N content of the soil was. Therefore, the N mobilized by leguminous crops from the atmosphere would have been higher in past organic agricultural systems, a hypothesis that organic farming may well help to corroborate at present (Oberson et al. 2007). Despite these uncertainties, we have carried out the preliminary estimates shown in Table 4.4.

Table 4.4. Estimates of N added to the soil by leguminous crops in Sentmenat towards 1861-1865

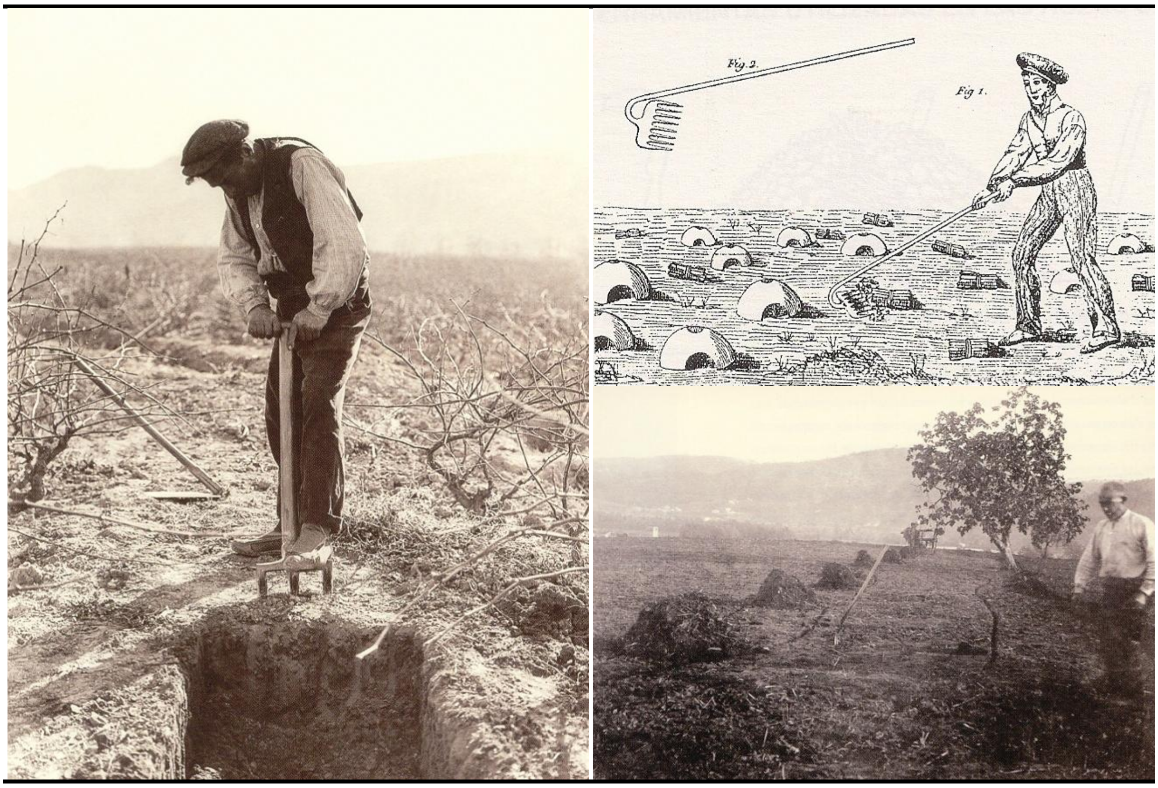
	estimated N average fixation kg ha^{-1} year^{-1}	cropland sown ha year^{-1}	%	N incorporated kg year^{-1}
Beans	34.5	23.5	15.2	810.8
Alfalfa and other forages	26.2	65.7	42.4	1,720.3
Peas	20.0	65.7	42.4	1,304.4
TOTAL	Weighted average: 24.8	154.9	100.0	3,835.5

Source: our own, based on the N-P-K composition per unit weight of the legumes used in our balance (Tisdale and Nelson 1956; LaRue and Patterson 1982; Phillips and DeJong 1984; Wilson 1988; Peoples and Craswell 1992; Drinkwater et al. 1998; Holland et al. 1999; Domburg et al. 2000; Berry et al. 2003; Schmidtke et al. 2004; Oberson et al. 2007; Bassanino et al. 2007; Castellanos et al. 2009; Loomis et al. 2011) and the other references given in Table 8.

Green manure provided another important use of leguminous N-fixing properties. We have found enough historical sources to believe that green manures were already used in the province of Barcelona during the second half of the 19th century, and were widely supported by agronomists of that period. However, we do not have precise data of the average area sown, the species used or the amount of atmospheric N fixed. As a very preliminary rough estimate, and assuming that 3.6% of herbaceous cropland was sown yearly with green manure, about 165,900 kg of aerial biomass may have been buried into the soil. We assume that the atmospheric N fixed was the only net input flow from green manure that must be included in the balance sheet, since the rest of the nutrients are simply recycled into the soil.

According to many local contemporary authors and sources, some amounts of crop by-products and forest biomass were directly applied to the soils as fertilisers, besides using them as compost matter in the manure pile. Two procedures were employed: 1) a direct burial of fresh vegetal matter in ditches dug between rows of vines; 2) ploughing into the soil ashes, charcoal and topsoil burnt in the so-called «*hormigueros*»(Miret 2004).

Figure 4.3. Biomass buried in a ditch dug between vines (left) and fertilising*hormigueros* (right)



Sources: the photographs were taken during the 1930s in Catalonia (Roca-Fabregat 2008), the engraving on the top right was printed in France in 1827 (Miret 2004).

How many nutrients could be obtained with these fertilising methods? In order to estimate the local biomass potential, the proportion between land sown with grains, land devoted to arboriculture and the available biomass that could be removed from woodland or scrubland was analysed. The amount of nutrients which were added to the soil by the fresh burial of biomass is easy to infer from its N-P-K content (although only the organic N is taken into account disregarding any possible loss by mineralization). The amount of nutrients supplied by each *hormiguero* has been taken from Olarieta et al. (2011). It seems that any net N contribution would have been negligible but the *hormigueros* would have added some amounts of P and K, which could also result in a significant yield increase of legumes intended to supply N (Johnston 1991).

Apart from that, there remain some unknowns still about the impact this method may have had in the biotic component of soil fertility.According to the interpretation given by the agronomist Cristobal Mestre and the chemist Antonio Mestres in 1949, the rise in temperature experienced by the topsoil covering the *hormiguero* caused a variation in the populations of soil micro-organisms that may help to explain the harvest increases obtained in experimental fields fertilised in this way compared with control plots—for example, by increasing free atmospheric N fixation (Mestre and Mestres 1949). Our own preliminary estimate is shown in Table 4.5.

Table 4.5. Estimates of nutrient added to the soil by burying fresh biomass and burning piles of *hormigueros* in Sentmenat towards 1861-1865

Nutrients	Available matter in kg	N *kg* year^{-1}	P *kg* year^{-1}	K *kg* year^{-1}
Biomass from pruning buried	497,590	2,141.6	1,181.2	1,754.2
Biomass from woodland or scrub buried[a]	111,522	557.6	167.3	669.1
hormigueros burnt and ploughed[b]	1,472,509	0.0	30.3	606.3
TOTAL FROM BIOMASS	2,081,621	2,699.2	1,378.8	3,029.6

[a]Mulch, grasses, acorns, branches or bushes that could also be partly used to burn in *hormigueros*, along with pruning and other by-products of crops. We have assumed that only a quarter of the available biomass in woodland and scrubland was used in this way. [b]We have considered the maximum potential number of *hormigueros* according to the available biomass. Source: our own from Cussó, Garrabou, Olarietaand Tello(2006A), and results of fieldwork and analysis performed by José Ramon Olarieta.

We assume that the burial of biomass and the *hormigueros* played a role of filling the remaining gaps in the nutrient balance. They appear in our balance sheet as a minor component because the number of *hormigueros* estimated is small, due to the considerable uncertainties that still prevail about the size of each *hormiguero* and the amount of biomass burnt in it. Acknowledging that this issue deserves to be further studied in future, we have taken as a cautionary option an average figure of 13 *hormigueros* per cropland hectare per year (or 20 if only applied to vineyards), a figure adjusted to the forest biomass locally available—while figures up to 200 (Roca-Fabregat 2008) or even 700 per hectare per year (Barón de Avalat 1780) can be found in some historical sources. Taking into account the high intensity of labour demanded by these techniques, it seems reasonable to assume that their use would depend on the relative scarcity of other fertilisers and the abundance of cheap labour. We came to a similar conclusion considering the role played by the task of removing fallen branches and dried biomass from the Mediterranean forests and scrubland, which usually become prone to wildfires (Pyne 1997; Grove and Rackham 2001).

5. An organic nutrient balance close to equilibrium?

In Table 4.6 the nutrients taken by crops, or lost through other processes, are confronted with two different estimates of their replacement by various fertilising methods: a) a maximum potential amount of N-P-K which the mass balance tells us should be somewhere in the local agro-ecosystem; and b) the fraction we believe was actually put into the soil discounting material losses by these fertilising methods: manure piles, cesspools, latrines, *hormigueros*, burial of fresh biomass, crop legumes or green manure. This balance is not aimed at assessing accurately each nutrient flow moved by livestock, agricultural labour and natural processes. Some minor flows have been omitted, like erosion losses which could be largely offset by the accumulation of sediments in other nearby lands—depending on the scale of analysis. Nor have we assigned values to the mineralization processes in the soil, or the possible increase obtained in atmospheric N fixation by stimulating free bacterial activity through piles of *hormigueros*. But even admitting a margin of error, which can only be reduced through future calibration and comparison with other balances, we believe that the usefulness of this assessment lies in its heuristic function.

Table 4.6.Annual output and input flows of nutrients in cropland of Sentmenat towards 1861-1865

4.6.1. Nutrient content of material flows (N, P, K in kg per year)

	content of N	content of P	content of K
1. Natural atmospheric deposition	1,132	0	1,455
2. N fixation by free bacteria in the soil	7,584	0	0
3. Seeds	769	140	205
4. Total manure available	12,164	3,892	10,704
5. Manure finally applied to the soil	6,082	3,776	8,563
6. N fixation by leguminous plant grown	3,835	0	0
7.Nutrients buried by green manure	1,371	116	912
8. N atmospheric fixation by green manure	973	0	0
9. Other biomass buried	2,699	1,349	2,423
10. Available human sewage	7,030	1,268	1,914
11. Human sewage finally applied	3,515	1,230	1,531
12. Household and village garbage	664	918	566
13. *Hormigueros* burnt and ploughed	0	30	606
I=1+2+3+5+6+8+11+12+13			
I.INPUTS ACTUALLY DRAWN	27,253	7,443	15,349
A. Losses by natural processes	9,049	0	2,051
B. Nutrients extracted by crops	20,195	5,971	14,332
II. NUTRIENTS REMOVED (A+B)	29,244	5,971	16,383
Balance with the inputs actually applied (I-II)	-1,991	1,472	-1,034

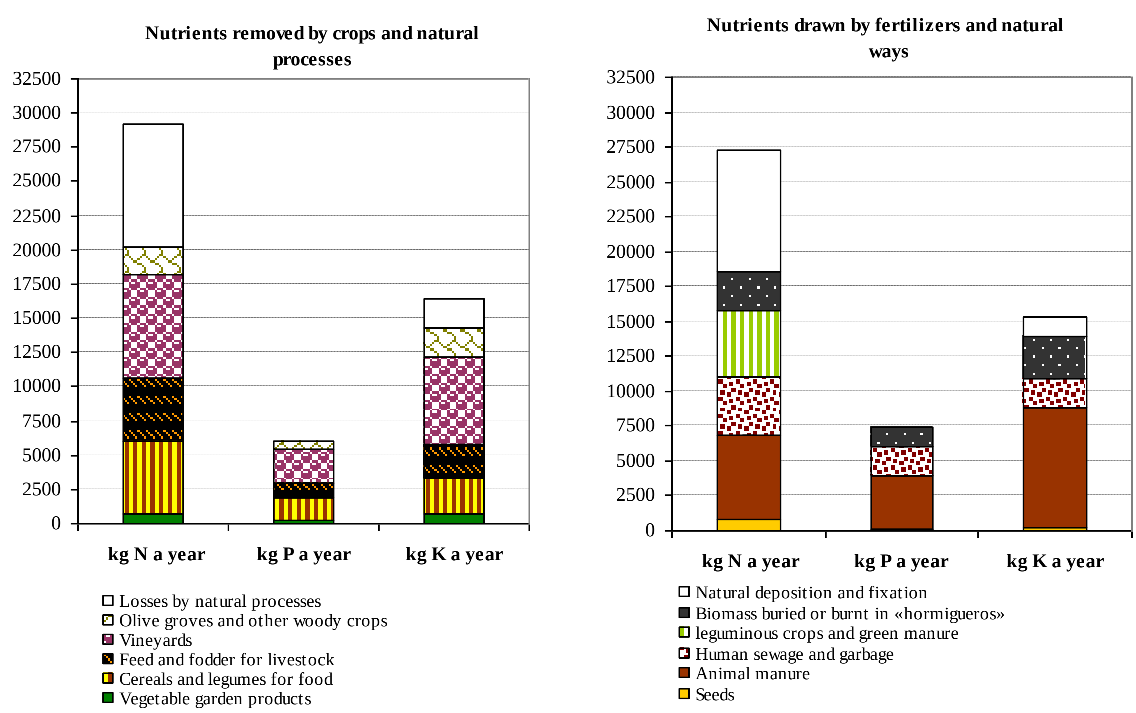
4.6.2. Nutrient flows per unit area (kg ha^{-1} year^{-1} of N, P, K or in % of total removed)

	N ha^{-1}	%N	Pha^{-1}	%P	K ha^{-1}	%K
1. Natural atmospheric deposition	0.7	3.9	0.0	0.0	0.9	8.9
2. N fixation by free bacteria in the soil	4.7	25.9	0.0	0.0	0.0	0.0
3. Seeds	0.5	2.6	0.1	2.3	0.1	1.3
4. Total manure available	7.5	41.6	2.4	65.2	6.6	65.3
5. Manure finally applied to the soil	3.8	20.8	2.3	63.2	5.3	52.3
6. N fixation by leguminous plant grown	2.4	13.1	0.0	0.0	0.0	0.0
7.Nutrients buried by green manure	0.8	4.7	0.1	1.9	0.6	5.6
8. N atmospheric fixation by green manure	0.6	3.3	0.0	0.0	0.0	0.0
9. Other biomass buried	1.7	9.2	0.8	22.6	1.5	14.8
10. Available human sewage	4.3	24.0	0.8	21.2	1.2	11.7
11. Human sewage finally applied	2.2	12.0	0.8	20.6	0.9	9.3
12. Household and village garbage	0.4	2.3	0.6	15.4	0.4	3.5
13. *Hormigueros* burnt and ploughed	0.0	0.0	0.0	0.5	0.4	3.7
I=1+2+3+5+6+8+11+12+13 I.INPUTS ACTUALLY DRAWN	16.9	100.0	4.6	100.0	9.5	100.0
A. Losses by natural processes	5.6	30.9	0.0	0.0	1.3	12.5
B. Nutrients extracted by crops	12.5	69.1	3.7	100.0	8.9	87.5
II. NUTRIENTS REMOVED (A+B)	18.1	100.0	3.7	100.0	10.1	100.0
Balance with the inputs actually applied (I-II)	-1.2	-6.8	0.9	24.7	-0.6	-6.3

Source: our own based on the previous tables.

We think that this balance sheet helps us to reveal some basic features of the societal attempts made to close the flow of nutrients in a highly intensive organic agriculture of a Mediterranean-type. Despite the inaccuracies and uncertainties it allows us to obtain some results. First, the amount of nutrients available to sustain cropland fertility could have been nearly large enough to replace the main macro-elements taken from the soil by crops and natural processes, provided that the processing efficiency of animal manure and human sewage was not lower than 50% in N, 90% in P and 80% in K. We suppose as well a high labour intensity allocated to make *hormigueros* or bury fresh biomass in order to import nutrients –mainly K— from uncultivated areas to cropland.

Figure 4.4. Summary of the nutrient balance in the municipality of Sentmenat in 1861-1865.



Source: our own based on the previous tables.

As seen in Figure 4.4, should these assumptions be changed –for example by considering a loss higher than 50% of N content in manure management and reuse of sewages— the whole amount of nutrients extracted would not have been replenished. On the other hand, we know that N losses in manure piles could be reduced up to only 30%, if the floor of stall was paved and compost process was accurately managed, according to the results obtained by the agronomist José Cascón (1918) in a Spanish experimental farm. Anyhow, we are not assuming that actual fertilisation always balanced crop extractions in each farm or plot. A very important aspect, which is masked in average figures, is to what extent social inequality meant a different availability of livestock manure, woodland or scrubland cuts, and latrines. In spite of the fact that the maximum potential of fertilisers available was probably enough not to undermine soil fertility, we believe that poor winegrowing tenants did so to some extent due to the lack of access to them. Inequality was the problem, not the capacity of organic fertilisation.

This first result can be interpreted in the light of what Barry Commoner (1971) considered to be a basic principle of an ecosystem's functioning: everything goes somewhere. In an organic-based agricultural system, these places where nutrients went were not far away. Our balance shows, for example, that a share of K was obtained from burying or burning biomass in *hormigueros*. Thus, any remaining K gap could probably have been closed by increasing labour and biomass allocated to make them. When looking at figures 4 and 5 there appears another important issue that deserves to be stressed. The proportion of cropland devoted to grow feed and fodder could be kept relatively low thanks to the role played by agricultural reuses and natural pastures in livestock feeding. This material eco-efficiency required a careful integrated management between cropland, uncultivated land and livestock breeding—which was also a key for the corresponding energy efficiency (Cussó et al. 2006a; Cussó et al. 2006b).

6. Discussion

These results fit with the degree winegrowing specialization reached in Sentmenat towards 1860-65. Two-thirds of the cropland acreage devoted to vineyards brought about a significant saving of N and P. The import of 1,556 Hl a year of wheat, together with some amounts of salted fish and rice, meant an annual gain of 2,561 kg N, 433 kg P and 459 kg K which accumulated in sewages. While the N content in the wine exported was negligible, the P taken yearly from wine was around 414 kg and the K around 2,070 kg. Thanks to that, the nutrient trade balance led to a net gain of some 2,561 kg N a year and 433 kg P, together with a net loss of 1,611 kg of K a year. Therefore, the apparent sustainability this maximum availability of nutrients that existed somewhere in Sentmenat allowed would have also relied on that N gain against a slight loss of P and K (Tello et al. 2006; Tello et al. 2008b; Garrabou et al. 2010; Badia-Miró et al. 2010).

However, the full potential of nutrients available in the local agro-ecosystem was one thing, and the ability to collect and reintroduce them into croplands was another. Most of our uncertainties arise when the difference between potential and actual nutrient availability becomes apparent. Bearing in mind the abovementioned processing losses of animal manure and human sewages, we reach a second conclusion: the actual availability of animal manure and human wastes would cover only 33% of N, 84% of P and 62% of K required to replace the extractions made by crops. Therefore, sustaining cropland fertility would depend on whether other forms of organic fertilisation could cover this gap. Two of them stand out: the symbiotic N fixation by legume crops, and their use as green manure, which could have covered about 16% of extractions; and the K obtained by burying fresh biomass or burning it in *hormigueros*, which should have covered about 14% of the K required in order to balance the local agro-ecosystem in 1860-65.

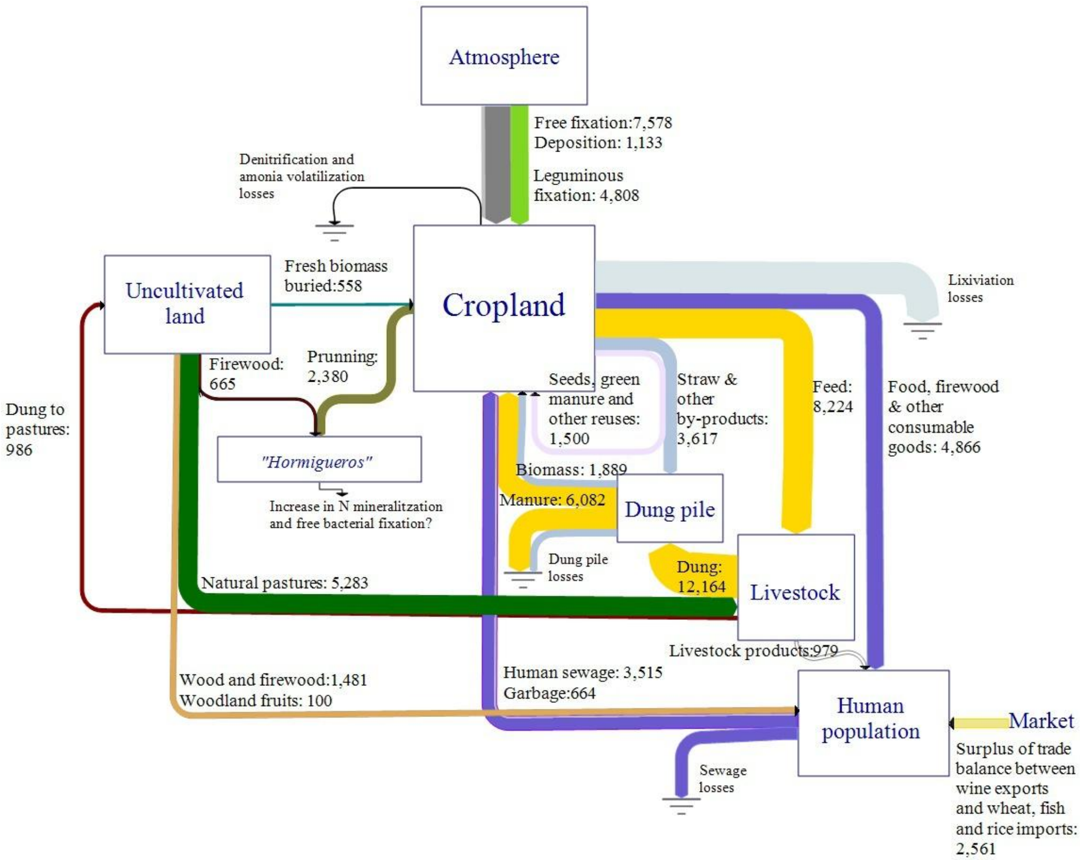
In other words, despite the agronomists' cries about the inadequacy of livestock densities kept and manure applied being true, other options were available for a Mediterranean-type of intensive organic agriculture to recruit some of the nearby nutrients. Nevertheless, these alternatives were highly labour-intensive. Hence, we reach a third conclusion: the main limiting factor to obtain organic nutrients was not biophysical, but technical and economic. Instead of the maximum potential of N-P-K available in the agro-ecosystem, what mattered most was the actual capacity to recruit them as fertiliser considering the chain of losses experienced in dung piles, latrines, cesspools, sewers or *hormigueros*. A key limiting factor was the amount of human labour and animal work needed for that purpose.

There were, of course, some ultimate agro-ecological limits inherent to any organic-based agrarian economy wishing to increase yields without overshooting the renewable resources available at a local or regional scale. Before reaching these limits some possibilities to increase leguminous crops and use them as green manure remained, which in 1860-65 covered just one quarter of cropland. Here again the limiting factors appear to be more economic than agro-ecological. The Mediterranean water stress had to be overcome somehow, but this could be done to some extent increasing the water retention capacity of soils by increasing their organic matter content, or with temporary and permanent irrigation. Another option was to specialize in arboriculture, a practice that requires less water and extracts fewer nutrients from the soil. However, all these alternatives needed land improvements and labour investments, and these in turn had opportunity costs according to the relative market profitability of their alternative uses.

Fourth, the scope for increasing agricultural yields through more intensive organic fertilisation was very limited unless land-uses were changed in the direction pointed out by agronomists, i.e. increasing the land sown with leguminous crops and using them as green manure or increasing forages, livestock and manure. Anyhow, up to a point these land-use changes clashed either with the rainfall limitations of the Mediterranean environment, or with the actual market opportunities to reallocate land towards commercial woody crops (González de Molina 2002; Guzmán and González de Molina 2009; González de Molina et al. 2010b; Vanwalleghem et al. 2011).

Finally, the nutrient balance of Sentmenat in 1860-65 shows a crucial aspect that deserves to be emphasised: the maintenance of cropland fertility was only possible through a permanent transfer of nutrients from uncultivated areas of woodland, scrub and pasture. This was of course an overriding feature of any past organic-based agricultural system. What draws most our attention in this case study is the smaller role played by livestock in that transfer, compared to the key role played by human labour in cropping legumes and green manure and transferring nutrients from woodland or scrub by means of *hormigueros* burnt and biomass buried into cropland. Livestock only moved a small part of it, while manpower had to do the rest. This was a key feature of Mediterranean organic agricultures, which contrasted with other European bioregions (Figure 4.5).

Figure 4.5. Annual flows of N in the cropland area of the municipality of Sentmenat towards 1861-1865 (kg)



Source: our own based on the previous tables. The flows from market are based on historical dietary information (Cussó and Garrabou 2003).

Therefore, we come to our fifth and last conclusion: organic fertilisers alternative to animal manure played a key role –albeit small in absolute terms— in transferring nutrients from uncultivated areas into cropland. Besides being highly labour-intensive, these transfers imposed a relevant nutrient tribute on woodland or scrubland, mainly in terms of K, which added to the simultaneous extraction of timber, firewood or charcoal. The maintenance of cropland fertility was closely related to the sustainability of this multiple-use of forests, which up to a point might have been overexploited. Photographs taken during the first third of the twentieth century show an apparent low forest cover remaining. At that time woodlands were reduced to a minimum in Catalonia, and even more in Spain: forest land occupied only 15% of the country area in 1915 (Tello and Sudrià 2011), or about 20% in 1955 (Schwarzlmüller 2009).

Table 4.7: Summary of the estimations and sources

Item	Source	Estimation
1. Natural annual atmospheric deposition	MOGUNTIA model at Holland et al. (1999)	0.7 kg N/ha
2. N free annual fixation by bacteria in the soil	Loomis et al. (2011). Berry et al. (2003)	1-5 kg N/ha
Livestock average live weights	Livestock census of 1865 and the assumptions used in Cussó, Garrabou, Olarieta, et al. (Cussó et al. 2006b)	Cattle: 371 kg Horse and Mule: 326 kg Donkey: 172 kg Sheep: 30 kg Goat:34 kg Pig: 77kg Poultry: 2 kg
Daily average manure production per head of livestock	Aguilera (1906), Cascón (1918)	Horse and Mule: 22kg Donkey: 8 kg Cow: 34.2 kg Sheep and goat: 2.3 kg Pig: 6.5 kg Poultry: 0.137 kg
4. Manure composition (fresh weight).	Cascón (1918), Tisdale and Nelson (1956)	0.50%N 0.16%P 0.44%K
4 and 11. Losses during biomass composting, manure and human sewage storage manure piles.	Cascón (1918), Aguilera (1906), Urbano-Terrón (1989)	50% N or 30 % N 0.3% P 20% K
Manufactured fertilisers.	Garrabou and Planas (1998)	Small capacity of manufacturers. Tiny imports of guano and industrial fertilisers. So we consider none.
6 and 8. N symbiotic fixation.	García-Ruiz et al. (2012)	N content coming from atmosphere: 60% N content in grain: 3.5 % N content in aerial biomass: 62% N content in roots: 33% N deposited into the soil by roots: 18% of the total N fixed
10 and 12.Garbage and	Mataix (2003)	

human sewage.	Tarr (1975), Schmid-Neset (2005), García-Faria (1893)	Garbage: 57 Kg/inhabitant
13. Hormigueros	Olarieta et al. (2011)	- The soil cover of the *hormiguero* comes from the same cultivated area. - Each *hormiguero* is made with an average of 68 kg of woody biomass. - As a result of the combustion we have 2.5 kg of char and 2.5 of ashes. - The composition of the ashes from the *hormiguero* is the same as if the same type of woody biomass were burnt elsewhere. - They are made in equal parts of pruning and woodland or scrub cuts.
A. Average natural losses	Drinkwater et al. (1998), Galloway et al. (2004), Kosmas et al. (1997), Rana and Mastorilli (1998), Rosswall and Paustian (1984), Tisdale and Nelson (1956), Torrent et al. (2007)	Leaching: 5.5 kg N/ha Denitrification: 1.5 kg N/ ha irrigated Ammonia volatilisation: 5% green manure N inputs
B. NPK composition of nutrients extracted by crops	Soroa (1953), CESNID (2003), Mataix (2003). Moreiras-Varela et al. (1997)	

Source: our own based on the previous tables. (Item number corresponds with the numbers in table 4.6)

Chapter 5. Making bread from stones?[1] Regional nutrient balances and socio-ecological transition in North-East of Iberian Peninsula (Catalonia c.1920)

“[...]la cosa es que no entiendo lo qué tengo que decirle, directamente no entiendo el potasio, no entiendo por qué no entiendo que a lo mejor no es importante, no entiendo que todo eso solamente me caiga a mí, me haga tanto mal a mí aquí sola, aquí con el café que se va a enfriar si no me apuro.”

(Cortázar 2009)

1. Introduction

1.1. The Socio-EcologicalTransition of industrialisation

Socio-Ecological Transitions are the gradual changes in the society-nature interactions that bring together another regime of energy and materials consumption (Krausmann et al. 2008; Krausmann and Fischer-Kowalski 2013). From the sociometabolic regimes described by Sieferle (2001) industrialisation is the only one that decoupled the supply of energy from land related biomass and human labour on land (Krausmann et al. 2008). This was accompanied by new environmental problems, together with uncertainty on the perdurability of the model itself as the use of stocks of fossil fuels involve only a 'temporary emancipation from land' (Mayumi 1991).

The industrialisation of agriculture involved the linearisation of the process by increasing the flow of inputs and decreasing the recycling flows. Although by doing this, industrial agriculture shortened the separation between labour time and productive time—an observation already done by Marx for agricultural production—still, natural processes have to occur (Mann and Dickinson 1978), as, obviously, not all inputs are human-driven. These natural processes are reinforced by traditional agricultural methods used both in past and current non-industrial agricultures[2]: diversity of cultivars, maintenance of functional biodiversity, recycling of biomass and nutrients, use of organic matter and covering soils

[1]We make reference to the saying: "Los catalanes de las piedras hacen panes".

[2]Indeed, nowadays non-industrialagriculture provides livelihood at least to two million people worldwide (van der Ploeg 2014).

(Altieri 2004). From an agroecological perspective[3], industrial agriculture is unsustainable as long as it undermines the ecosystem structures and processes that make possible agriculture itself.

Focussing only on Agrarian Metabolism, González de Molina (2010) described the Socio-Ecological Transition in three waves that affected agroecosystems at different scales and elapsed at different rhythms depending on the world region. In Europe, the first wave started during the nineteenth century, when the urban-industrial sector, the increasing population and the liberal reforms all together pushed the agricultural production over the capacity to restore fertility by organic means. The introduction of synthetic fertilisers at the end of the nineteenth century[4] marked the start of the second wave, which neglected the land cost of fertilisation[5](Guzmán and González de Molina 2009), besides the increasing costs of recycling urban waste. Indeed, the treatment of fertility loss and pollution concentration in rural and urban areas respectively as two independent problems was strongly criticised by some agronomists, hygienists and thinkers of the time—Liebig and Marx among them—(Marald 2002; Foster 2004).

Besides the recycling of organic matter of any origin, the three main organic means to restore the nutrients extracted through harvest were additions of manure from livestock, fixation of atmospheric N through leguminous plants and deposition of N—all of them will be detailed below. Livestock needs grain, forages and pastures, consequently competing for land with humans. Forage plants need to be flowering to enhance its nutritional potential for livestock; this is a disadvantage for arid climates because as plants tend to grain before, they can be cut less times. Synthetic fertilisers were net entries of nutrients that allowed overcoming these constraints. Nevertheless the use of synthetic fertilisers were not free from controversy, although yields increase with the introduction of synthetic fertilisers, diminishing returns in N applications in cereals have been demonstrated recently (Tilman et al. 2002). Therefore to maintain soil fertility, not only balanced fertiliser applications are needed, also crop rotations, reduced

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[3]Other dimensions of unsustainability of agriculture emerge when studying different perspectives, see for example Friedmann (2011), Giampietro (1997b) or Schneider and McMichael (2010).

[4] Ammonia synthesised by the Haber-Bosch process was not among the synthetic fertilisers accounted at the beginning of the European Socio-Ecological Transition in agriculture.With the temporal exception of Germany during the World War I, it was not until after the 1950s that the expanded worldwide contribution importantly incremented yields (Smil 2001).

[5]There were other land saving technologies such as concentrated feed, cattle selection and seeds breeding that probably followed the same pattern as the spread of synthetic fertilisers, however the data is much less complete, see van Zanden (1991).

tillage, cover crops, fallow periods and manure (Tilman et al. 2002). This is true as long as 'soil health' is the true source of fertility (Doran 2002). Despite recognising that balanced fertiliser applications are not the only dimension of fertility, the importance of the approach from González de Molina (2010) is that there was not enough organic fertilisers in order to maintain or increase the agricultural produce without mining the fertility of soils. Indeed, fertility was a major concern in agriculture at the end of the nineteenth and the beginning of the twentieth centuries, especially in more arid areas, such as the Mediterranean (González de Molina 2002).

During the nineteenth and the beginning of the twentieth centuries in Spain, it was common place to say that, in spite of regional differences, there was not enough livestock densities to produce the manure needed in fields (Simpson 2003). Consequently, we found the idea of complementarity between both organic and synthetic sources of fertilisers in the work of a number of Spanish agronomists at the beginning of the twentieth century. There were suggestions to reinforce the recycling of biomass from a variety of industries: sugar, fisheries, preserves, winery, oil, leather or wool; not to mention other practices such as green manures, *redileo, majadeo* or the spread of preparations of human excrements, garbage or ashes (Llorente and Galán 1910; Cascón 1918; García-Luzón 1922; Rueda-y-Marín 1934). Other more imaginative practices included the use of algae and a detailed process to capture locusts during a plague using ditches and a treatment of the dead bodies consisting in toasting, eliminating fats with benzene and compacting them (Soroa 1929). At the same time, all of them recommended farmers to calculate the flows of the main nutrients—nitrogen, phosphorus, potassium and sometimes calcium and iron—or make an analysis of soil composition and add purchased synthetic fertilisers to the available organic fertilisers.

In the preceding chapter (Tello et al. 2012) we calculated a nutrient balance in a municipality c.1860, when synthetic fertilisers were not spread. Moreover, we did not have enough data to follow the nutrient flows in other (more arid) municipalities or smaller scales, but we concluded that, probably, to balance the soil nutrients some crop types such as vineyards had to be short of nutrients. We aim to lengthen in time and scale that study by doing another case study circa 1920, to figure out to what extent were organic and synthetic fertilisers important for the maintenance of fertility. By that time, the agrarian systems in Catalonia would be situated in between the first and the second wave according to González de Molina (2010). In addition, we want to use data from other areas with different aridity and human settlement patterns to identify regional differences.

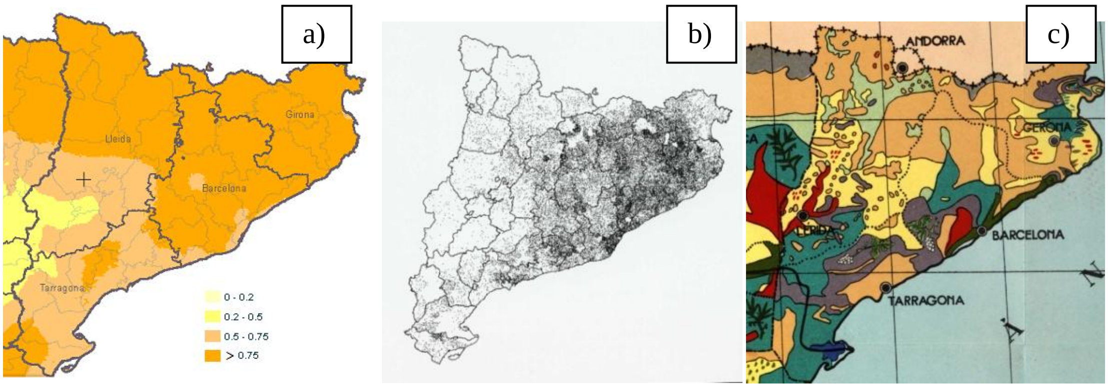
Following this introduction, in the next subsection 1.2, we describe the region of study. After that, this chapter is organised as a working paper detailing methodological and data issues. Hence, in section 2 we explore limitations and potentialities of the methodology of calculating nutrient balances. In sections 3 and 0, we calculate the flows of nutrients extracted and applied to cropland. In these sections we stress on the details of the calculations that differ from our main methodological reference—(Garcia-Ruiz et al. 2012)—, in addition we depict criticism of sources and specify the way in which we solved the limited availability of data. In section 7, we present the balance and discuss its meaning. Finally, in section 8 we situate our conclusions within the framework of the Socio-Ecological Transition described in the previous subsection 1.1. This chapter is accompanied by a series of Annexes. The first two are recompilations of NPK compositions, these are Annexes 2.A and 2.B. Annex 2.C details the value of the main nutrients flows for each region. Lastly, Annex 2.D summarises the main sources used to quantify each of the flows of extraction and addition.

1.2. Agro-climatic and socioeconomic features of the three main Catalan regions

As a rule of thumb, Catalonia can be socio-ecologically split into two according to its climatic conditions, Wet and Dry whose limit is the annual precipitation of 500 mm (Garrabou et al. 2001a), which coincides with the aridity index i.e. the occurrence of periods when precipitation is lower than the evapotranspiration created by high temperatures (Figure 5.1.a). This limit matches with the historical settlement pattern (Figure 5.1.b), approximately coinciding with the limits of the Islamic Empire until the XII century, when the 'New' Catalonia was conquered by Christians fast enough to approach the land concentration that occurred in some areas of the South of Spain. Unlike the previous conquest of the lands between the Pyrenees and the Llobregat River, which was slow and uncertain, and required peasant repopulation. As a result, the agrarian landscape of 'Old' Catalonia was configured by *masies* (Figure 1.b). Coming from the Latin word *manere* (to inhabit), this Catalan type of scattered rural habitat was a pattern of isolated farmhouses surrounded by compact units of polycultural land of some five to twenty or more hectares. Their occupiers used to be serfs under feudalism, but after the peasant revolts of the late Middle Ages (*Remensa* Wars) they enlarged their *masies* thanks to the Black Death and got control over the forthcoming land-use intensification thus becoming wealthy landowners in many cases.

These regions approximately match with the current administrative units, therefore the provinces of Barcelona and Girona belong to Old or Wet Catalonia, whereas Tarragona and Southern Lleida with New or Dry Catalonia. Admittedly the Northern part of Lleida use to be classified as part of the Old or Wet Catalonia, however its proximity to the Pyrenees involves a completely different landscape and settlement configuration. As a result, this can be considered a different historical and geographic region from the other two. Contrarily to the other two regions, the Pyrenees have a sizable area of pastures, which is related to the other two regions of Catalonia, through the seasonal migration of livestock «*trashumancia*». At the south of the Pyrenees, the plains of Lleida province, used to be dry-farming cereal lands during the nineteenth century. Its low and unstable yields, large fallow lands and small livestock densities were similar to the Interior region of Spain (Garrabou et al. 1995; Simpson 2003). Conversely, at the end of the nineteenth century in Old Catalonia, fallow land was substituted by rotations that integrated leguminous forages, mainly sainfoin (Saguer and Garrabou 1995b). Taken as a whole, the cereal yields of Old Catalonia were between two and three times those of the plain of Lleida, thus comparable to other advanced agricultures of North Europe (Garrabou et al. 1995).

Figure 5.1. Images of Catalonia



a) aridity index: annual Precipitaion/Potential EvapoTranspiration (P/PET), capture from Ministerio de Agricultura Alimentación y Medio Ambiente [284]; b) *Masies* of Catalonia in 1860, capture from Ferrer i Alòs et al. (2003); c) Approximated delimitation of the main crops in the Iberian Peninsula, capture from DGA (1933: 364).

2. Methodological challenges and responses to calculate nutrient balances in historical farm systems

The purpose of accounting for the nutrients flows of a system—a method called indistinctively nutrient balance or budget— used to be twofold. To increase the efficiency of fertiliser applications and/or to calculate the emission from farmland (i.e. cropland and livestock only, as non-cultivated land areas used to be excluded) due to fertiliser or slurry over application (Öborn et al. 2003). In addition, some authors use nutrient balances to quantify alternative sources of fertiliser, e.g. household waste, in those places where farmers cannot purchase them from the market (Kanmegne et al. 2006; Hayashi et al. 2012). The main nutrients studied are the main nutrients used as synthetic fertilisers i.e. nitrogen, phosphorous and potassium (N, P and K), with a special focus on N, due to the effect of some of its chemical forms in the Green House effect and acid rain. In addition, the release of N and P to water fosters the eutrophication of waters with the ensuing biodiversity loss.

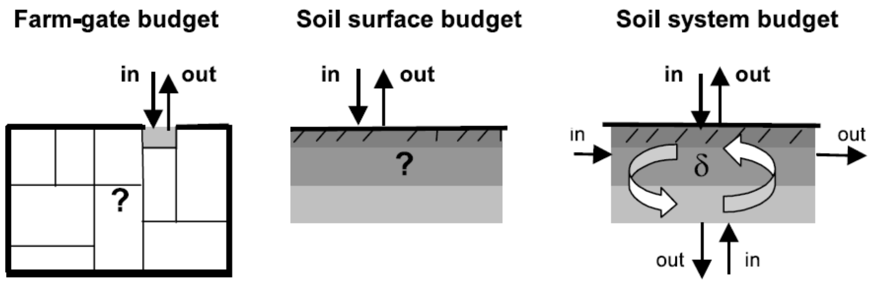
Both the system boundaries—e.g. soil of cropland, gate of farm, human settlements, industry, agro-food system, etc—and the scale—e.g. farm (cropland, livestock or both together), regional, national, etc—vary depending on the purpose of the analysis. Concerning only agricultural production systems, Oenema et al. (2003) made a review of several nutrient budget accountings, and grouped them into three types (*sic*), i.e. according to three main conceptualizations of the system (Figure 5.2).

Farm-gate budgets, measure the nutrients in the products that go in and out of the farm i.e. manure and livestock purchased would be inputs but not manure produced within the farm; outputs would be exports of harvested products, also milk and meat.

Soil surface budgets, account the nutrients that cross the soil surface. Any product harvested would be an output, but not reactions such as ammonia volatilisation, which should be adjusted before accounting for the inputs.

Soil system budgets, add the recycling or the loss of nutrients within the soil system to the accounting.

Figure 5.2. Conceptual differences in boundaries and nutrients flows



"Conceptual differences in boundaries and nutrient flows of farm-gate budget, soil surface budget and soil systems budget. The view from above for the farm-gate budget shows that nutrients enter and leave the system via the farm-gate, while the vertical direction of nutrient flows into and out of the soil for the soil surface budget is emphasizes via a vertical soil cross-section. Three-dimensional nutrient flows, including nutrient recycling and changes in nutrient stock characterize soil system budgeting." Source: from Oenema et al. (2003: 5).

The choice of scale and system boundary will define the data acquisition strategy, hence the precision of the input-output ratios of the nutrient balance (Oenema et al. 2003). In our case of regional scale, we had to rely mainly on official databases, whose expected critical points of data availability were described in Sacco et al. (2003) through their proposal for a methodology of regional nutrient balance for an Italian case. Yet, as they used the farm-gate approach, they did not account for what Garcia-Ruiz et al. (2012) called «natural inputs» e.g. atmospheric deposition, free N fixation, etc, which were a fundamental piece in past organic agricultures. This is an additional critical point to those described by Sacco et al. (2003) as due to lack of regional data, we had to extrapolate field data or values from literature to regional scale, which is controversial. For instance, Burke et al. (2002) tried to include these natural inputs at regional scale, but eventually excluded atmospheric N deposition and important N exports such as leaching and denitrification due to lack of empirical data for the Great Plains. As an integrated solution, Oenema et al., (2003) assessed biases and errors and quantified uncertainties, but still we did not use them in this study because they were focused on N budgets of current agroecosystems in The Netherlands.

The versatility of the methodology complicates comparisons between different balances and the interpretation of the results should always be accompanied by the context i.e., surplus or balance of nutrients does not mean environmental damage *per se*. The system could storage or dissipate the excess of nutrients e.g., soils with low soil fertility could increase the storage capacity by a continuous surplus of nutrients. This was precisely the basis of the model of increase in yields in English agriculture, due to long term assimilation of N through convertible farming and rotations of leguminous crops (Allen 2008). Also, although it is not usually contemplated, the time elapsed affects the quantity of nutrients balanced (Öborn et al. 2003). For instance: adding a fertiliser with N soluble form in rainy seasons will lead to high N losses through leaching; manure has less N in soluble forms than synthetic fertilisers, so some of the N will be uptaken by the current harvest and some will remain for the next harvest.

Beyond the limitations for comparison, are the implications of taking into account the nutrient balance as the only dimension of fertility. Thus, Koning and Smaling (2005) reflected the utility and limitations of regional nutrient budgets applied to policy making and the inconvenience of neglecting other dimensions, such as the dynamics of world markets, or the rehabilitation of agricultural knowledge services to the design of policies of soil alleviation in Africa. In addition, (Olarieta et al. 2008) warned about the reductionism involved in the identification of the accountancy of nutrient flows as if they were the only dynamic of soils affecting agrarian productivity—although they were focused in the criticism of monetary valuation methods of soil degradation. This can lead us to the fallacy that chemical fertilisers can replace soil fertility, without taking into account the role of organic matter. Not in the least, soil organic matter is a "complex bio-organo-mineral system" (Manlay et al. 2007) indispensable for the biological soil functioning—and so biogeochemical cycles and mineralisation— and cation-exchange capacity (Manlay et al. 2007; Feller et al. 2012). Furthermore, there are recent studies relating the influence of compost in the prevention and treatment of some plant diseases (Litterick et al. 2004). Unfortunately this is far from the scope of this study, as to estimate the soil organic matter c.1920, is something that cannot be done through a nutrient balance.

Considering these limitations, how can the numerical values of a nutrient balance be interpreted? Up to this point, it is clear that we have to refer to our own purpose and context of our case study. Hence, to refine our aim presented in section 1.1, we study the loss of soil nutrients as a driving biophysical force, lead by economic driving forces and social agencies, in the transition of Mediterranean organic agricultures to industrial agriculture. Our time-period—circa 1920—is, in between the first and the second wave of the Socio-Ecological Transition (González de Molina 2010). Accordingly, lands were forced to yield with non-existent or very low external entries of nutrients.

In the previous chapter (Tello et al. 2012), we found that in the village of Sentmenat, of Barcelona province circa 1860, the nutrient flows were balanced for most of cropland area thanks to the variety and combination of nutrient sources. However, from historical sources we know that vines, as well as other wooden crops such as olive groves were not fertilized at all. These typical Mediterranean non-irrigated wooden crops allowed annual harvests without fallow or fertiliser applications (González de Molina 2002).

Although, in Catalonia vineyards could not be considered a monoculture (Garrabou et al. 2001a), its achearage grew continuously since the XVII century until it boomed, peaked and collapsed due to the grape phylloxera plague at the end of the nineteenth century. After that, vineyards were only recovered in those places where they were grown previous to 1850 (Badia-Miró et al. 2010; Badia-Miró and Tello 2013). Notwithstanding, the post-phylloxera vines turned into a different crop that needed more inputs due to its shorter lifespan and its higher vulnerability to diseases such as downey or powdery mildew; hence they started to be fertilized, in all probability insufficiently. We do not know what happened since 1860 or in other areas of Catalonia concerning the fertility of soils, but everything points to a trend of soil nutrient deficiency, mainly concentrated in cropland such as those where vineyards were cultivated. This gives us a hint to interpret the results of the balances: surpluses will not be a concern for an environmental load at regional level (as it is currently for the area) and deficiency will be interpreted as a constraint to enhance or maintain cropland soil fertility.

As we said above, scale, boundaries and data to build a nutrient balance depend on the purpose of the balance. Consequently, we followed the "Guidelines for Constructing Nitrogen, Phosphorus and Potassium Balances in Historical Agricultural Systems" (Garcia-Ruiz et al. 2012), as they coincide with our purpose and approach. They shown data sources and the difficulties in reconstructing nutrient balances for past organic agroecosystems and then applied them to a local case in the South of Spain. Notwithstanding, our calculations differ on some points. We lacked some of their starting data: the manure applied was unknown, so we estimated it through a series of steps shown in section 4.1. In addition, we decided to contribute to their proposal by calculating the N losses related to the application of fertiliser (denitrification, ammonia volatilisation and leaching) as we explain in subsection 3.4, we did this because we lack regional data.

Finally yet significantly, two were the flows that we could not include in our accountings: entries by soil formation and nutrient losses by erosion of surface soil horizons. Although georeferenced data on bedrock and soils could be found in ICGC *(Institut Cartogràfic i Geològic de Catalunya*)[6], the reconstruction of a

[6] http://www.igc.cat

detailed map to allocate each crop c. 1920 for the entire Catalonia was far from the scope of this study. Yet this omission would not affect significantly the balance: in Mediterranean regions weathering of the bedrock has low intensity (Garcia-Ruiz et al. 2012). Moreover, due to the habit of terracing the vineyards erosion values should be lower than those reported for olive groves in the South of the Iberian Peninsula (Vanwalleghem et al. 2011; Infante-Amate et al. 2013).

3. Extractions

3.1. Cropland area

The report "*Avance estadístico de la producción agrícola en España : resumen hecho por la junta Consultiva Agronómica de las memorias de 1922 remitidas por los ingenieros del Servicio Agronómico Provincial* " (JCA, 1923) gives the most complete information of agricultural produce at province scale among all the reports from the beginning of the twentieth century in Spain[7]. Even some of the crop types are disaggregated by Partido Judicial, which was the next smaller administrative division at that time.

We grouped the crops described into 12 crop types (Table 5.3) to facilitate the analysis. By «Grain» we mean cereal and leguminous crops for grain production, we also split Grain between «irrigated» and «rainfed». This last category included all the non-irrigated crops, for instance cereal under dry-farming conditions, most vineyards, carob and olive trees or maize in the most humid areas. By «Forage» we refer to «*praderas artificiales*» a common term in Spanish statistics to name leguminous and non leguminous crops such as clover, alfalfa, rye, oat, sorghum, etc. These are usually irrigated with aerial parts cut at one or more times when they bloom, these are used as fodder in its fresh form or as hay. Other crops, «Industrial» were strongly linked with local industry, such as hemp for fibres or sugar beets. «Rice», «Oranges» and «Hazelnut trees» were already known but new in the intensive way they started to be cultivated at the beginning of the twentieth century (Calatayud 2006). The rest of the categories coincide with those from the report.

Fallow land was not included as a single category as the source used considered it as part of the rotations of rainfed Grain. Table 5.1 shows a high disparity between provinces, while fallows were almost half of the cereal land in Lleida, in Girona

[7] David Soto, Universidad Pablo de Olavide, personal communication.

they did not even exist. Although these numbers could have some logic, they seem rather extreme and we know from GEHR (1991) that Spanish fallow data was unreliable before1929. However, not having other data to compare with, we used them. Yields did not take into account fallow land; although we included it in total cropland area.

Table 5.1. Fallow land area in each province.

	Total fallow land «barbecho blanco and erial no permanente[8]» (ha)
Barcelona	3,500
Girona	0
Lleida	149,000 (only 32% of it belongs to irrigated cereal and leguminous land, the rest is rainfed)
Tarragona	340

Source: JCA (1923)

Nevertheless, the main challenge was not related to fallow but to the allocation of crop types due to the split of the province of Lleida into dry plain and Pyrenees to make it match with the regions described above. Some of the produce data (tomatoes, capsicums, plums, almonds, olive trees and vines) were disaggregated in JCA (1923) into *Partido Judicial*, a lower administrative unit that allowed us to differentiate between Plain and Pyrenees. The first cropland map for Spain was not published until 1933 (DGA 1933), it had low resolution and of course was not georeferenced (Figure 5.1c). Notwithstanding, it provided valuable information when we estimated the share of herbaceous crops (65 and 35% respectively). Moreover, with "*Medios que se utilizan para sumministrar el riego a las tierras y distribución de los cultivos de la zona regable*" (JCA 1916), which reports the area irrigated by each waterway, we could estimate the location of irrigated land. The channels of Urgell, Aragón, Cataluña and Pinyana were the most important waterways from the Segre River to the plain of Lleida, together they covered 90% of the irrigated land in Lleida province.

Forages were rotated with other crops, they were more common in the plains and mostly consumed within the province excepting alfalfa, which was sold to Barcelona or Tarragona to feed livestock used in industries (JCA, 1914). Consequently we considered a larger share in the Plain than in the Pyrenees (82% and 18% respectively), as always according to the shares of DGA (1933). We cross checked the total cropland area calculated in this way with the one we

[8] This was the original in Spanish.

calculated using the livestock census of 1917 (JCA, 1920). It reports total cropland together with total pastures and forests per *Partido Judicial*, and both sources coincided (see Table 5.3). According to this same source, the 84% of meadow, forest and scrub land of Lleida was in the Pyrenees.

Table 5.2.Partidos Judiciales considered in each region of Lleida province

Lleida Plain	Lleida Pyrenees
Balaguer	Seud'Urgell
Borges Blanques	Solsona
Cervera	Sort
Lleida	Tremp
	Viella

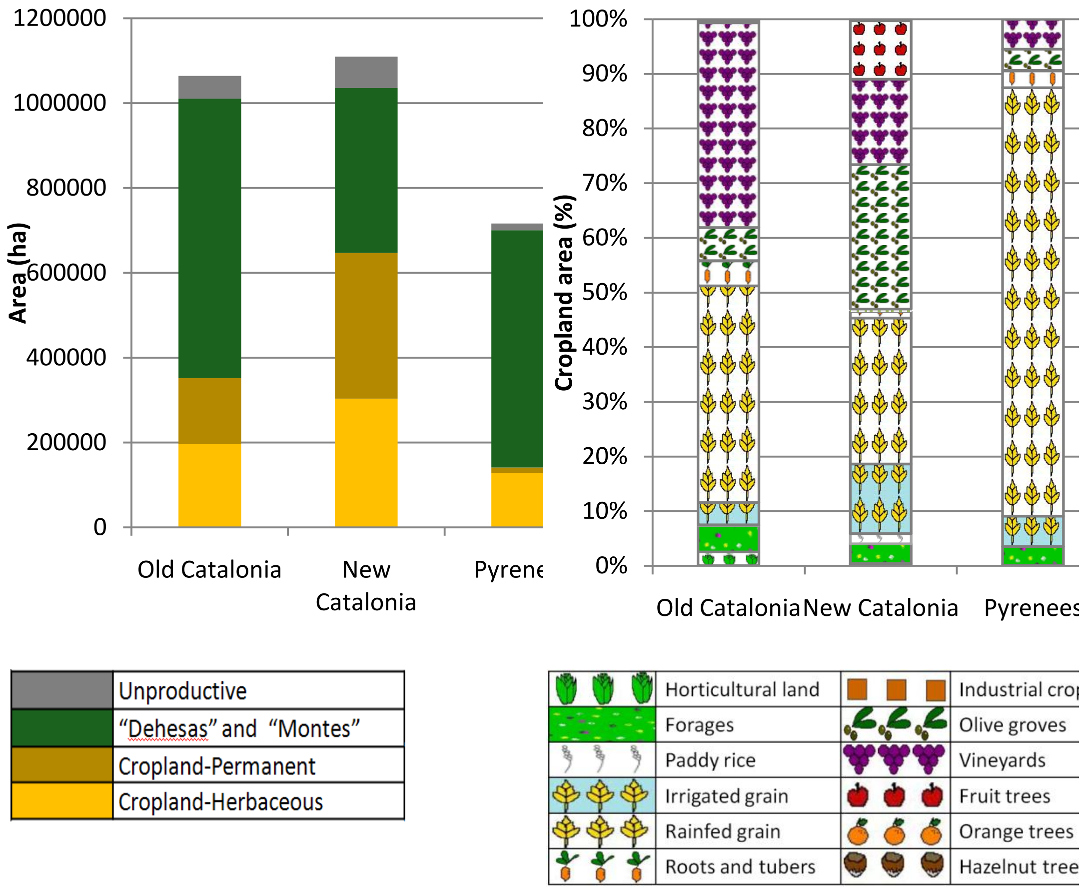
Table 5.3. Our estimation of the cropland area of the two historical and climate differentiated areas of Lleida province

	Lleida Plain (ha)	Lleida Pyrenees (ha)	Source
Irrigated grain	70,527	7,836	
Rainfed grain	154,916	90,983	DGA (1933)
Roots and bulbs	6,059	3,558	
Horticultural land	1,299	132	JCA (1923)
Industrial	1,378	153	JCA (1916)
Forages	16,134	10,756	Adjusted according all the data
Olive trees	98,057	5,463	
Vineyard	21,144	7,766	JCA (1923)
Fruit trees	2,348	47	
Total	371,862	126,694	
Total cropland using the aggregated ration from f JCA (1917)	361,346	137,210	

Sources within the table.

The land and cropland types of each region are represented in Figure 5.3. The total area of the Pyrenees is considerably smaller than the other two, with the highest share of forest but the same share of herbaceous crops per total area as Wet Catalonia. The near absence of permanent crops contrasts with the other two regions, where the area of permanent wooden crops is akin to herbaceous crops. Vineyards and olive groves were the main permanent crop; also, fruit trees were important in New Catalonia. Unlike other parts of Catalonia, on the plains of Lleida province, 26% and 31% of olive groves and vineyard land were irrigated. However as the source did not specify respective yields, we could not make any distinction in Figure 5.3, yet we took these irrigated lands into account when accounting for nutrients added by irrigation. Other crop types where located in specific areas, hence the rice fields in New Catalonia were in the delta of the Ebro River. In addition, the horticultural lands in Old Catalonia were mainly concentrated in a belt around the cities of Barcelona and Girona.

Figure 5.3. Total area and cropland distribution per crop type.



Note: Fallow rotation is considered as Cropland-herbaceous and irrigated/rainfed grain according to the source. Source: JCA (1923) and to split the land data from the province of Lleida we used those sources specified in Table 5.3.

3.2. Agricultural produce

JCA (1923) registered edible parts of plants grown in horticultural land, legume and cereal grains, straws, aerial mass of forage plants, roots and tubers, fruits from trees together with wine and oil production[9]. Among the possible by-products, only winery and oil pomaces were fully registered. Prunings from vines and olive trees were included as well, either in monetary or weight units, but the amounts were clearly underestimated. This is due to the large area devoted to vines, overall in the province of Barcelona, which represents half of the total cropland (Figure 5.3) branches could represent a salient export of nutrients from cropland. However, the well-documented uses of vine by-products (Daneo 1921; Soroa 1929; Mestre and Mestres 1949) can be taken as a proof of its importance as feed for livestock or fertiliser (burned or buried fresh) in the same way as olive plantations (Infante-Amate 2011). We used the same estimations of annual pruning production asMarco et al. (forthcoming) see Table 5.4.

Other important sources of nutrients in past organic agricultures were parts of the plants remaining in fields, such as the underground biomass and stubbles, together with weeds, particularly if they belonged to the leguminous family (Garcia-Ruiz et al. 2012). In this case, the scale was too large to lose ourselves in the details that vary from crop type to crop type, especially taking into account that they actually do not leave the cropland area. This decision involved underestimating the total N losses, as some should be attributed to the decomposition process.

Table 5.4. Prunings and other woody produce.

Wooden part	Prunings and other woody produce ($kg \cdot ha^{-1}$)
Fruit trees. Pruning	1,170
Olive trees. Pruning	1,935.6
Olive trees. Shoots	554
Vine trees. Pruning	1,341.6
Vine trees. Uprooted	360
Vine trees. Vine shoots.	1,250

Source: Marco et al. (forthcoming)

[9] Different units were converted to tonnes. We asked current farmers from the province of Barcelona for weight equivalences of certain orchard products expressed in units such as bunch or dozen.

3.3. Nutrient content of harvested biomass

Previous studies dealing with nutrient balances in History for regions within the Iberian Peninsula (González de Molina and Guzmán 2006; Lana-Berasain 2010; Tello et al. 2012) used nutritional composition of produce types based on historical sources, mainly Soroa (1953). Whenever there was a lack of information, they used the composition of an equivalent product or completed the gap with data from current sources. The use of historical sources of nutritional values is problematic because data is often incomplete and/or lacking an explanation of the methods to obtain the values. Nevertheless, there are evidences showing that nutrient content of pre-industrial crops were higher, mainly due to two mechanisms that go together with the increase of yields. First, the so-called dilution effect, is due to the modification of environmental conditions such as increase of fertiliser, irrigation, etc., which leads to a decrease in the concentration of some minerals in dry matter (Jarrell and Beverly 1982). Some studies have shown this trend by comparing different historical nutrient databases, however as from one database to another there is a number of uncontrolled variables and uncertainties, stronger analysis cannot be performed (Mayer 1997).

The second one depends on the genetic characteristics of the more yielding new varieties, as Davis (2009:19) explains: “In fruits, vegetables, and grains, usually 80% to 90% of the dry weight yield is carbohydrate. Thus, when breeders select for high yield, they are, in effect, selecting mostly for high carbohydrate […] thus, genetic dilution effects seem unsurprising.” Hence, when growing low and high-yielding cultivars for the same crop type with the same environmental conditions, the latter would have less concentration of nutrients. This was the case when a long straw variety of wheat was compared with a semi-dwarf wheat cultivar bred since the sixties in the Broadwalk experiment of Rothamsted (Fan et al. 2008). Although these are interesting and useful results, studies confirming genetic dilution are limited to the study case—a single crop type and a specific place—so a general trend cannot be identified: “Results from the present study suggest that the Green Revolution has unintentionally contributed to decreased mineral density in wheat grain, at least following the Broadbalk Experiment.” (Fan et al. 2008).

Coming back to our dilemma about using current or historical nutrient values, we resolved to use historical nutritional data from Soroa (1953). This data set has limitations since water content and sources are absent. These limitations are those from historical quantitative data: the source is unknown and if measurement were made, the instruments and techniques could be less accurate than the ones used nowadays. On the other hand, nitrogen content in plants is highly sensitive to fertilisers applications (Gauer et al. 1992). As in our case, synthetic fertiliser applications were low, we therefore preferred to use this data instead of more accurate or new data. In addition, it would make our balance comparable to the previous ones cited above. When the nutritional data was not available in Soroa (1953), we used values from modern sources (see Annex 2.A).

3.4. Nutrient losses (denitrification, ammonia volatilisation and leaching)

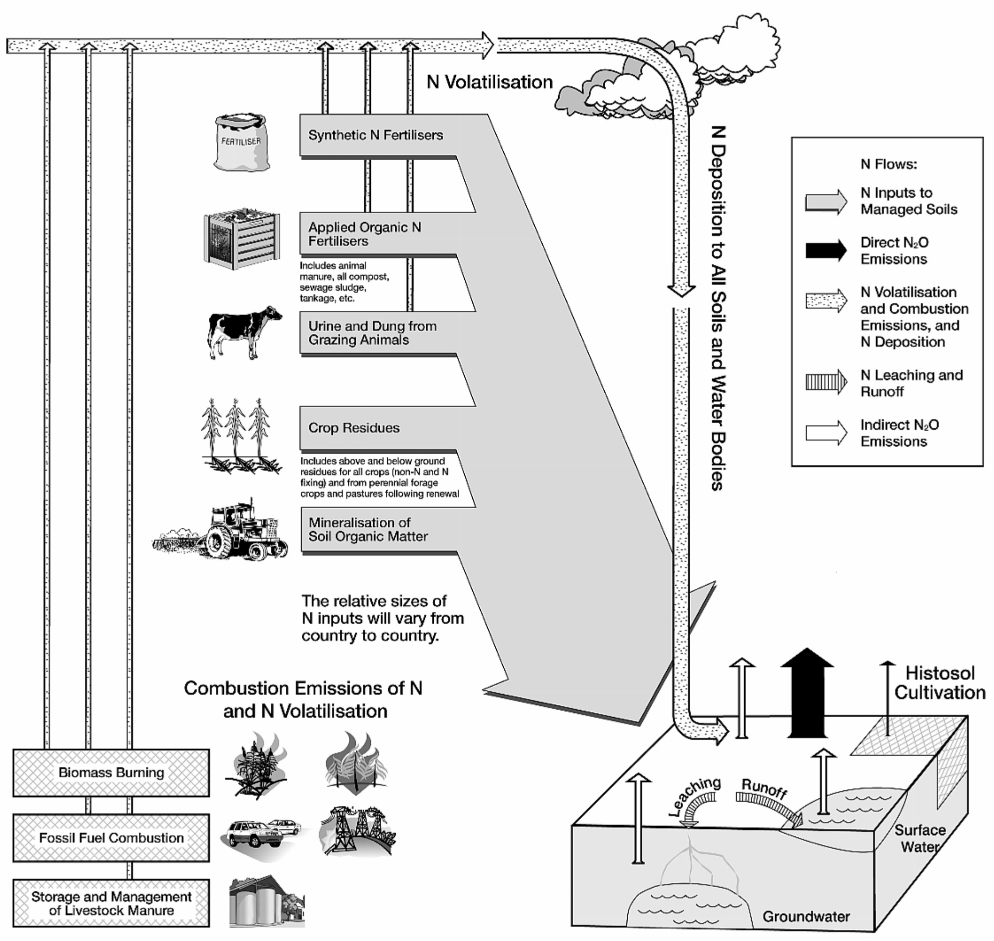
Garcia-Ruiz et al. (2012) offered ranges for emissions of nutrients to the atmosphere or water bodies calculated or measured from their case studies at municipal scale. Nevertheless, as we used a broader scale, we decided to follow the methodology described in International Panel for Climate Change (IPCC 2006) for the emissions of nitrogen.

The IPCC is the international body for the assessment of climate change. The United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) established it in 1988. It works as a scientific body joining and assessing all the published data related to climate change, and then writing reports for commitment in the decision making process of the state members. So, the procedures described in the "Guidelines for National Greenhouse Gas Inventories"(IPCC 2006) are based on an extended literature review to quantify the greenhouse gases emissions from anthropogenic sources.

Related to agriculture, the management of manure (in dry lots, pits, addition of other organic matter, etc.) and the management of agricultural soils (amount of manure applied, tillage, soil moisture, pastures, etc.) are the two groups of practices that release nitrogen in one form or another[10]. Among all the greenhouse gases that IPCC (2006) describes, our interest is in nitrous oxide (N_2O). They called 'direct emissions' those that produce N-N_2O and 'indirect emissions' (see Figure 5.4) those that produce gases that eventually raise the levels of tropospheric N (N-NH_3, N-NO_x and N-N_2). By skipping the step that turns N-x into N_2O we could account for total N emissions.

[10]IPCC considers that emissions from unmanaged land are very low compared to those induced by anthropogenic activities. They consider that “the so-called 'background'emissions estimated by Bouwman (1996) (i.e., approx. 1 kg N_2O–N·ha^{-1}·yr^{-1} under zero fertiliser N addition) are not “natural”emissions but are mostly due to contributions of N from crop residue. These emissions are anthropogenic and accounted for in the IPCC methodology” IPCC (2006: 11.10).

Figure 5.4. Schematic diagram illustrating the sources and pathways of N that result in direct and indirect N2O emissions from soils and waters.



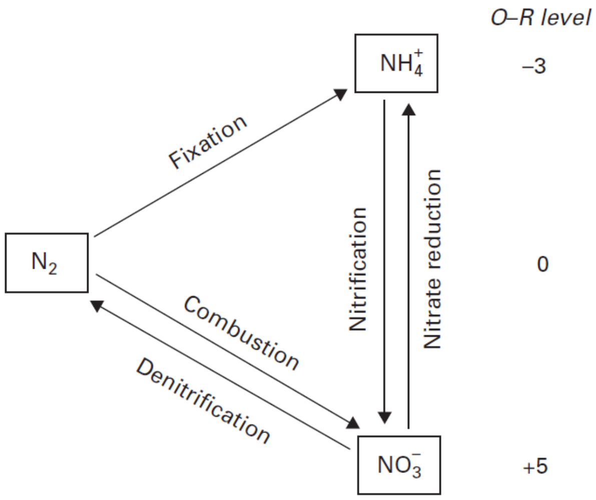
Source: from IPCC (2006:11.8).

Regarding the emissions of other nutrients, we did not take into account the P and K leaching losses included by the storage of manure due to the low rain averages at provincial level and, as we know from historical sources, farmers rarely moisturised manure heaps. P and K leaching would be significant, as some authors have reported (Michel et al. 2004) with water doses higher than the rainfall in the regions studied.

3.4.1. N emissions through storage

Emissions from manure storage depend on the initial nitrogen and carbon content, the duration of the storage and its type of management. Direct N_2O emissions occur via combined nitrification and posterior denitrification of nitrogen contained in manure. Nitrification is the oxidation of ammonia nitrogen to nitrate nitrogen (Figure 5.4) and does not occur under anaerobic conditions. Denitrification is an anaerobic process transforming nitrites (NO_2^-) and nitrates (NO_3^-) to nitrous oxide (N_2O) and dinitrogen (N_2) (Figure 5.5). "There is general agreement in the scientific literature that the ratio of N_2O to N_2 increases with increasing acidity, nitrate concentration, and reduced moisture. In summary, the production and emission of N_2O from managed manures requires the presence of either nitrites or nitrates in an anaerobic environment preceded by aerobic conditions necessary for the formation of these oxidised forms of nitrogen. In addition, conditions preventing reduction of N_2O to N_2, such as a low pH or limited moisture, must be present." IPCC (2006 10:52).

Figure 5.5. Scheme of the oxidation and reduction processes of N



"Oxidation–reduction levels of nitrogen in nitrate (NO_3^-) and ammonium (NH_4^+) ions and dinitrogen gas (N_2) and the transformations between these important levels. Nitrite (NO_2^-) lies at +3 in most pathways to and from nitrate but has been omitted for simplicity." from Loomis et al. (2011). Denitrification follows this sequence: $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$.

According to IPCC, indirect emissions of N_2O, result from volatile nitrogen losses that occur primarily in the forms of ammonia (NH_3) and nitrogen oxides (NO_x). The mineralisation to ammonia nitrogen (N-NH_3) of a fraction of the excreted organic nitrogen during manure collection and storage depends primarily on duration of storage, and to a lesser degree on temperature. However, simple forms of organic nitrogen such as urea (mammals) and uric acid (poultry) are rapidly mineralized to ammonia nitrogen (NH_3), which is highly volatile and easily diffused into the surrounding air from aqueous solutions in the form of ammonium (NH_4^+). These nitrogen losses begin at the point of excretion in houses and other animal production areas (e.g., milking parlours) and continue through the storage systems (IPCC 2006). Nitrogen is also lost through runoff and leaching into soils in the form of nitrate (NO_3^-) from the solid storage of manure at outdoor areas, in feedlots and grazing lands (IPCC 2006).

Table 5.5. Management types that can match with the common practices of Catalonia in 1922.

Dry lot	A paved or unpaved open confinement area without any significant vegetative cover where accumulating manure may be removed periodically. Dry lots are most typically found in dry climates but also are used in humid climates.
Deep bedding	As manure accumulates, bedding is continually added to absorb moisture over a production cycle and possibly for as long as 6 to 12 months. This manure management system also is known as a bedded pack manure management system and may be combined with a dry lot or pasture.
Solid storage	The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation.
Pit storage	Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility.

Source: from IPCC (2006: 10.62-64)

IPCC (2006) allows calculating denitrification, volatilisation and leaching from manure storage separately. Nevertheless, lacking specific data, we used the default values for all the aggregated nitrogen loss from manure storage (see Table 5.6), which combines all the forms of nitrogen released as explained above. The common management type of manure in our area c.1922 could match with three categories of those described in the IPCC report (2006), while the common disposal of human faeces in cesspits could match with the fourth one (see Table 5.5).

Table 5.6.Default values for total nitrogen loss from manure management

TABLE 10.23
DEFAULT VALUES FOR TOTAL NITROGEN LOSS FROM MANURE MANAGEMENT

Animal category	Manure management system [a]	Total N loss from MMS [b] $Frac_{LossMS}$ (Range of $Frac_{LossMS}$)
Swine	Anaerobic lagoon	78% (55 – 99)
	Pit storage	25% (15 – 30)
	Deep bedding	50% (10 – 60)
	Liquid/Slurry	48% (15 – 60)
	Solid storage	50% (20 – 70)
Dairy Cow	Anaerobic lagoon	77% (55 – 99)
	Liquid/Slurry	40% (15 – 45)
	Pit storage	28% (10 – 40)
	Dry lot	30% (10 – 35)
	Solid storage	40% (10 – 65)
	Daily spread	22% (15 – 60)
Poultry	Poultry without litter	55% (40 – 70)
	Anaerobic lagoon	77% (50 – 99)
	Poultry with litter	50% (20 – 80)
Other Cattle	Dry lot	40% (20 – 50)
	Solid storage	50% (20 – 70)
	Deep bedding	40% (10 – 50)
Other [c]	Deep bedding	35% (15 – 40)
	Solid storage	15% (5 – 20)

[a] Manure Management System here includes associated N losses at housing and final storage system.

[b] Total N loss rates based on judgement of IPCC Expert Group and following sources: Rotz (2003), Hutchings *et al.* (2001), and U.S EPA (2004). Rates include losses in forms of NH_3, NO_x, N_2O, and N_2 as well from leaching and runoff from solid storage and dry lots. Values represent average rates for typical housing and storage components without any significant nitrogen control measures in place. Ranges reflect values that appear in the literature. Where measures to control nitrogen losses are in place, alternative rates should be developed to reflect those measures.

[c] Other includes sheep, horses, and fur-bearing animals.

Source: from IPCC (2006:10.65)

Spanish agronomists at the time, used to describe the manure management systems as abandoned open air lots of manure where almost all nitrogen was lost, e.g.: "*Con esto se comprenderá que la mayoría de los estercoleros de la provincia son de los más rudimentario y primitivo. En algunos pueblos existen en medio de la calle. Por lo general en la mayoría de las fincas sólo aparece un espacio de tierra apisonada en donde se reúnen en un informe montón las deyecciones de los animales, las basuras y los deshechos de la granja, los orujos cuando su precio es bajo y todo cuanto no tiene una utilización directa*." (JCA 1920: 395). Therefore, we assumed the solid storage type as the most common practice, with an average of total nitrogen lost of 50%, ranging from 20% to 70% (Table 5.6). As losses are proportional to the N content, we used the average value of losses for all the cases. This is consistent with Loomis et al. (2011: 222), which calculated that decomposition in manure heaps lead to an aerobic process resulting in 50% losses of the original N. In dry climates, these losses were due to the volatilisation of the entire N in the form of ammonia. The next step according to procedure from IPCC (2006) is to calculate the losses of N remaining in manure following its application on fields, together with those derived from the application of other fertilisers and other management practices such as tillage.

In section 4.1 we obtained enough data to calculate the nutrients potentially applied through manure. However, to follow the methodology from IPCC (2006) it is necessary to separate between excrement and other materials in manure. The available data is for 'fresh' manure and never for excrements solely. This is so because to collect excrements and measure them agronomists needed bedding materials and some time to do it, thus some decomposition may occur. Not only do animal excrements have different compositions to bedding materials, they have different rates of nutrient losses, and that is why the methodology of IPCC argues to separate them. As we defined manure as livestock excrements plus other materials, to approximate the amount of excrements, we subtracted the weight of bedding materials and their nutritional composition is calculated in sub-section 4.4, while the data of fresh manure is show in subsection 4.2. These together with night soils and other organic fertilisers are the ones that suffered from storage losses (Figure 5.6, 5.7 and Appendix 2.C).

3.4.2. N emissions through land management

Managed land releases N through nitrification, denitrification, volatilisation and leaching—the same processes that affect manure— whose main pathways are illustrated in Figure 5.5. In soils, the reactions of nitrification and denitrification produce naturally nitrous oxide (N_2O), which ultimately is released to the atmosphere. Nitrification is the aerobic microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2) (Figure 5.5). The main limiting factor of these reactions is the availability of inorganic N in the soil.

The methodology from IPCC (2006), estimates N_2O emissions using human-induced net N additions to soils (e.g., synthetic or organic fertilisers, deposited manure, crop residues, sewage sludge), or mineralisation of N in soil organic matter following drainage/management of organic soils, or cultivation/land-use change on mineral soils (e.g., Forest Land/Grassland/Settlements converted to cropland). In addition, as the processes of volatilisation, leaching and runoff also affect the level of N in soils, the IPCC (2006) methodology also accounts for these flows IPCC (2006: 11.5-6). Sources of N volatilised are not only from fertilisers and from manures, but also include fossil fuel combustion, biomass burning, and processes in the chemical industry. The second pathway is the leaching and runoff from land of N from synthetic and organic fertiliser additions, crop residues, mineralisation of N associated with loss of soil C in mineral and drained/managed organic soils through land-use change or management practices, and urine and dung deposition from grazing animals. Where NO_3^- is present in the soil in excess of biological demand, e.g., under cattle urine patches, the excess leaches through the soil profile (IPCC 2006: 11.20).

Losses through land management are those resulting from the changes in soils due to anthropogenic interactions. These emissions relate to the application of synthetic and organic fertilisers, crop residues that remain in fields[11], urine and dung depositions by grazing animals, mineralisation related with the change of land use and drainage of soils. For our study, we considered only the emissions related to the application of fertilisers in cropland by following the equation 11.1 (IPCC: 11.7) for direct $N\text{-}N_2O$ emissions, i.e. denitrification. These means, like above, we followed the simplest methodology (the so-called Tier 1 in the guidelines of IPCC). Subsequently we did not consider different land cover, soil type, climatic conditions or more detailed management practices beyond that from the ones specified. Neither did we take into account any lag time for N direct emissions from crop residues, thus allocating these emissions to the year in which the residues are returned to the soil. The IPCC did not consider these factors because limited data are available to provide appropriate emission factors.

The value of denitrification depends mainly on the factor EF_2 (Table 5.7) that is multiplied by cropland area; however, it has a high range of uncertainty (2-24 kg $N\text{-}N_2O\cdot ha^{-1}$). In a different study, Hofstra and Bouwman (2005) reviewed a large number of cases and found that denitrification rates were lower on land with lower application of N and good drainage, which could be our case. Moreover, cropland values, with a mean value of 15 kg $N\cdot ha^{-1}$ and a median of 5 $kgN\cdot ha^{-1}$, were different from those of grassland of rice-flooded fields, with medians of 4 and 21 $kgN\cdot ha^{-1}$respectively. Due to the existence of exceptional cases, they reported the median as well as the mean. In addition, they even calculated a balanced median to correct unbalanced features of the data. The values were respectively: 3, 6 and 8 kg $N\cdot ha^{-1}$ and 17 for grassland, cropland, wetland rice and bare soil. So, in this case, following the recommendations from Hofstra and Bouwman (2005), we used a EF_2 factor of 5.

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[11]IPCC (2006) does not take into account the biological nitrogen fixation process itself as a direct source of N emissions. Thus, the N incorporations of N fixing crops were treated in the same ways as crop residues.

Table 5.7. Default emission factors to estimate N-N_2O emissions from managed soils.

TABLE 11.1
DEFAULT EMISSION FACTORS TO ESTIMATE DIRECT N_2O EMISSIONS FROM MANAGED SOILS

Emission factor	Default value	Uncertainty range
EF_1 for N additions from mineral fertilisers, organic amendments and crop residues, and N mineralised from mineral soil as a result of loss of soil carbon [kg N_2O–N (kg N)$^{-1}$]	0.01	0.003 - 0.03
EF_{1FR} for flooded rice fields [kg N_2O–N (kg N)$^{-1}$]	0.003	0.000 - 0.006
$EF_{2\,CG,\,Temp}$ for temperate organic crop and grassland soils (kg N_2O–N ha^{-1})	8	2 - 24
$EF_{2\,CG,\,Trop}$ for tropical organic crop and grassland soils (kg N_2O–N ha^{-1})	16	5 - 48
$EF_{2F,\,Temp,\,Org,\,R}$ for temperate and boreal organic nutrient rich forest soils (kg N_2O–N ha^{-1})	0.6	0.16 - 2.4
$EF_{2F,\,Temp,\,Org,\,P}$ for temperate and boreal organic nutrient poor forest soils (kg N_2O–N ha^{-1})	0.1	0.02 - 0.3
$EF_{2F,\,Trop}$ for tropical organic forest soils (kg N_2O–N ha^{-1})	8	0 - 24
$EF_{3PRP,\,CPP}$ for cattle (dairy, non-dairy and buffalo), poultry and pigs [kg N_2O–N (kg N)$^{-1}$]	0.02	0.007 - 0.06
$EF_{3PRP,\,SO}$ for sheep and 'other animals' [kg N_2O–N (kg N)$^{-1}$]	0.01	0.003 - 0.03

Sources:
EF_1: Bouwman et al. 2002a,b; Stehfest & Bouwman, 2006; Novoa & Tejeda, 2006 in press; EF_{1FR}: Akiyama *et al.*, 2005; $EF_{2CG,\,Temp}$, $EF_{2CG,\,Trop}$, $EF_{2F,Trop}$: Klemedtsson *et al.*, 1999, IPCC Good Practice Guidance, 2000; $EF_{2F,\,Temp}$: Alm *et al.*, 1999; Laine *et al.*, 1996; Martikainen *et al.*, 1995; Minkkinen *et al.*, 2002: Regina *et al.*, 1996; Klemedtsson *et al.*, 2002; $EF_{3,\,CPP}$, $EF_{3,\,SO}$: de Klein, 2004.

Source: from IPCC (2006:11.11).

As this is the case at the beginning of the twentieth century, we did not take into account the indirect emissions produced by cars and industry, which actually were very important at the end of the century (Galloway et al. 2004). Therefore, indirect emissions in this case are due to volatilised and then re-deposited nitrogen together with leaching, only from agricultural sources. As before, the uncertainty ranges of the default values (see Table 5.8) given in IPCC (2006: 11.24) are too wide, so we corrected them according to the characteristics of our study case, which is explained below.

In subsection 3.4.1 we already considered the maximum N losses by volatilisation in manure heaps, consequently we used the minimum value when applied to fields (Table 5.8). For dryland regions, where precipitation is lower than evapotranspiration throughout most of the year and leaching is unlikely to occur, the default FracLEACH (see Table 5.8) is zero. Thus, we should consider leaching from the fertiliser applied only in irrigated land. Nevertheless, by doing so we would be exaggerating this value because c.1920 irrigation doses were minimal, just to avoid crop failure (see subsection 5.3), the exception being horticultural land. Accordingly, we only calculated leaching in horticultural land. Unfortunately, we did not know the amount of fertiliser applied per crop type, and had to make a preliminary estimation according to JCA (1921).

The emissions due to land management are shown in Figures 5.6, 5.7 and Annex 2.C, while the storage and crop management emissions per cropland area are summarized in Table 5.9. These values are next to the global broad averages that Smil (1999) calculated for denitrification, leaching and volatilisation from fertilisers, around 18-29.6 kg N·ha^{-1} all together. The main difference is that he gave more importance to leaching losses (10-15 kg N·ha^{-1}) than us, which is consequent with the aridity of some regions of our case study.

Table 5.8. Default emission factors to estimate N-N2O emissions from managed soils due volatilisation and leaching.

TABLE 11.3
DEFAULT EMISSION, VOLATILISATION AND LEACHING FACTORS FOR INDIRECT SOIL N_2O EMISSIONS

Factor	Default value	Uncertainty range
EF_4 [N volatilisation and re-deposition], kg N_2O–N (kg NH_3–N + NO_X–N volatilised)$^{-1}$ [22]	0.010	0.002 - 0.05
EF_5 [leaching/runoff], kg N_2O–N (kg N leaching/runoff)$^{-1}$ [23]	0.0075	0.0005 - 0.025
$Frac_{GASF}$ [Volatilisation from synthetic fertiliser], (kg NH_3–N + NO_x–N) (kg N applied)$^{-1}$	0.10	0.03 - 0.3
$Frac_{GASM}$ [Volatilisation from all organic N fertilisers applied , and dung and urine deposited by grazing animals], (kg NH_3–N + NO_x–N) (kg N applied or deposited)$^{-1}$	0.20	0.05 - 0.5
$Frac_{LEACH-(H)}$ [N losses by leaching/runoff for regions where Σ(rain in rainy season) - Σ (PE in same period) > soil water holding capacity, OR where irrigation (except drip irrigation) is employed], kg N (kg N additions or deposition by grazing animals)$^{-1}$	0.30	0.1 - 0.8

Note: The term $Frac_{LEACH}$ previously used has been modified so that it now only applies to regions where soil water-holding capacity is exceeded, as a result of rainfall and/or irrigation (excluding drip irrigation), and leaching/runoff occurs, and redesignated as $Frac_{LEACH-(H)}$. In the definition of $Frac_{LEACH-(H)}$ above, PE is potential evaporation, and the rainy season(s) can be taken as the period(s) when rainfall > 0.5 * Pan Evaporation. (Explanations of potential and pan evaporation are available in standard meteorological and agricultural texts). For other regions the default $Frac_{LEACH}$ is taken as zero.

Source: from IPCC (2006: 11.24)

Table 5.9. Total N emissions due to manure storage and managed land per cropland area in the three Catalan regions

	N kg·ha^{-1}cropland
Wet Catalonia	26.4±3.3
Dry Catalonia	10.8±0.5
Pyrenees	10.5±2.1

Source: our own.

4. Addition

4.1. Manure

Some authors have estimated the amount of manure applied to Spanish cropland in previous studies. Gallego (1986) made an estimation of manure applied for the entire Spain and Simpson (2003) made an approximation by calculating livestock densities. However we preferred not to extrapolate these data because live weights and manure management varies from one region to another. Moreover, livestock type influences the nutrient content of manure. Therefore, we preferred to do our own estimation.

In the report "*Materias fertilizantes empleadas en la agricultura*" (JCA, 1921), provincial engineers of the state quantified the amount of any kind of material applied to agricultural soils in 1919. The amount of manure applied to fields is quantified by estimating the manure available per province, but the engineers who wrote the information did not indicate how they made these estimations. We have some reason to doubt its credibility for the provinces of Catalonia (see Table 5.10). First, the amount of manure for Barcelona province described in the annex is one order of magnitude higher than the one described in the text of the report. Second, according to the annex, manure production in Girona province is clearly underestimated as it had the highest livestock numbers (Table 5.13). Third, the numbers for Tarragona were so low that they were unbelievable.Our own estimation is compared with the JCA (1921) and shown in Table 5., the procedure for our estimate is described in the next subsections.

Table 5.10 Available manure for the four provinces of Catalonia, a comparison of data in JCA (1921) with our own estimations .

	According to the table from the annex (t)a	According to the text (t)a	Own estimation (t)
Barcelo	1,154,350	347,823	1,001,352±150,1
Girona	600,000	579,760	1,470,917±245,1
Lleida	977,451	--	1,267,349±186,8
Tarrago	4,160	--	288,418±59,925

The available manure of Barcelona reported in text differs from the value provided in the Annex of the same report. The numbers of Girona and Tarragona of the first column are too low given the livestock numbers shown in Table 5.. Source: a JCA (1921) and b our own elaboration explained in text.

4.1.1. Livestock numbers

Data on livestock numbers (Table 5.12) are from the livestock census closest to 1922, which is that of 1924 (MF, 1924). However, this census is very simple and it does not disaggregate livestock types nor give live weights. To solve this lack of data, we used the averaged live weights for the provinces from the next closer livestock census of 1917 (JCA, 1920), which had a higher level of detail and is even disaggregated by *Partidos Judiciales*. The averages of live weights per livestock type described are in Table 5.11.

Table 5.11.Live weights (kg·head^{-1}) in 1917 without corrections.

	donkey	horse	goat	swine	mule	sheep	cow
Barcelona	170	301	35	97	251	34	500
Girona	414	361	50	64	288	39	327
Lleida	245	372	50	73	332	38	369
Tarragona	300	350	40	150	350	24	550
Average	288	346	44	96	305	34	437

Source: JCA (1920)

Notwithstanding, we have reasons to think that some of the numbers presented in the census are not correct due to the exaggerated average weights of donkeys and cows. When cross-checking the live weights per *Partido Judicial* we found some unreliable data in the census and we discarded them, e.g. we found gigantic 2.5 t donkeys in La Bisbal (Girona). In addition, we found that the data provided by the agronomist from Tarragona was not accurate: he used the same weight for every

Partido Judicial and for the cases of donkeys, swine and cows values are so high that increased the total average. Provably he used the weight averages of adult animals to fulfil the survey, but adults are far from composing livestock populations only. Therefore, we substituted the values for Tarragona with the average of the other three provinces. See the changes in Table 5.12.

Table 5.12. Average of live weights (kg·head^{-1}) in 1917 corrected.

	donkey	horse	goat	swine	mule	sheep	cow
Barcelona	197	301	34	98	252	38	470
Girona	251	360	50	64	299	39	325
Lleida	241	387	50	71	335	38	406
Tarragona	230	350	40	78	350	35	400
Average	230	350	44	78	309	38	400

Source: JCA (1920).

Table 5.13. Livestock numbers (head) for Catalan provinces

	donkey	horse	goat	swine	mule	sheep	cow	total
Barcelona	9190	37760	48526	103948	13367	121317	23348	357456
Girona	4207	24658	35806	131901	15178	257577	64690	534017
Lleida	31451	11436	46799	68486	38256	278379	44554	519361
Tarragona	5609	4479	23855	55656	7930	21796	1659	120984

Source: MF (1924).

As an overview, we calculated the livestock densities per cropland area (Table 5.14), where the highest values being in Girona seek an explanation. Besides being on average, the rainiest of the provinces, the settlement pattern allowed the breeding of livestock, as each *masia* had typically some area devoted to forest or pastures. In addition, in the mountain areas, where there were no *masies*, the existence of larger areas of pasture gave the opportunity to raise cattle at a greater scale. Moreover, the first decades of the twentieth century brought an increase in crop intensification and in the growth of legumes such as sainfoin and alfalfa to produce hay. Even the census of 1917 describes the situation of the livestock production in the province of Girona in terms of prosperity: "*la industria ganadera revista verdadera importancia en la provincia, encontrándose actualmente en estado de gran prosperidad bajo el punto de vista industrial, ya* *que a las favorables condiciones de producción y alimentación con que se cuenta, van unidas las económicas por la demanda de sus productos en los diferentes mercados*" (JCA, 1920: 265).

This is the opposite described for Tarragona province: "*Es tan escasa la importancia de la ganadería en esta provincia que puede considerarse figurando en uno de los últimos lugares entre las de España, a causa de que sus condiciones agrológicas favorecen los cultivos en tal forma que ocupan la mayor parte de las tierras cuya superficie es laborable."* (JCA, 1920: 217). In other words, Tarragona lacked the pastures to maintain big livestock, which were concentrated in the Delta of the Ebro River to work on rice fields. Sheep and goats where spread around the province, using the leaves of vineyards and cereal shoots as feed.

The situation of Tarragona was similar to the plains of Lleida, where the low livestock numbers were used as draft animals. In the Pyrenees the small ratio cropland/pasture allowed more livestock densities. In the centre of the province of Barcelona swine, raised for the meat industry, were the dominant livestock. Horses and mules were important as a labour force in the areas with more industry. The groups of goats sparsed in the surrounding forest areas of the city of Barcelona were of some importance as their milk was sold to the city "*constituyendo pequeña industria rural*"(JCA, 1920: 181).

Table 5.14. Livestock densities for 1917 and 1924 in the four provinces of Catalonia

	[a]Livestock densities 1917	[b]Livestock densities 1924
Barcelona	17	40
Girona	72	85
Lleida	19	24
Tarragona	13	9

Note: densities are in Livestock Units of 500 kg · km^{-2} of cropland. Source: [a] JCA (1920) and [b] JCA (1920) for live weights, MF (1924) for livestock numbers and JCA (1923) for cropland area.

Obviously, the livestock densities were not homogenous within the provinces. The census of 1917 which disaggregates by *Partidos Judiciales* shows the dramatic concentration of livestock per cropland area in the one that included the city of Barcelona (188 LU500kg·km^{-2} cropland). If it had been taken separately, the rest of the province would have had an average livestock density of 14 LU500kg·km^{-2}cropland. The comparison between the two years denotes a dramatic increase of livestock density in the Barcelona province. There, the number of heads of livestock increased rapidly, especially draft livestock, i.e. mules and horses, which almost doubled. If this was due to the increase within the city of Barcelona or in other places of the province is something that we cannot know from the 1924 census.

4.2. Manure production

The next step was to estimate the manure produced by livestock. Probably the best way to do it would be through diets and livestock produce (e.g. milk, meat, etc.), making a material balance of the livestock subsystem, which would give more complexity to the balance. It is not by chance that the integration of livestock management with the management of both cropland and uncultivated land is the main key point to close the nutrient balance at a local scale. Some examples of livestock diets are described in the census of 1917 (JCA, 1920). More examples can be found in the book "*Alimentación de los animales*" (Rossell i Vilà 1929), written by a well-known Catalan veterinarian of the time, Pere Màrtir Rossell i Vilà. His book was based on the "Scientific feeding of animals" (Kellner, 1915 [1909]) by the German agronomist and livestock nutritionist Oskar Johan Kellner. However, these reports show diets that refers to 'good practices', which were not necessarily followed `in practice´. To confirm if these recommended diets were reliable using the local means we would have to estimate the produce of pastures, control for the migrating of livestock and verify the livestock produce. Similar to our calculations with straw (subsection 4.2), we could calculate if the produce of forage and feed was enough to fed livestock at least at the Catalan level, and then estimate or find trade data of feed and hay. However, this would be a titanic task for this paper and therefore, we left it for upcoming research. The following steps describe the process we followed to calculate the production of manure.

José Cascón Martínez was a well-known Spanish agronomist at the beginning of the twentieth century, who specialised in the cultivation of Castillian rainfed cereals. In his book "*El estiércol y la alimentación animal*" (Cascón 1918) he measured the amount of fresh manure as well as the bedding materials for the years 1909 to 1915. He studied four livestock types: horses, sheep, bovine and swine (Table 5.15); all from the experimental farm (*Granja Agrícola de Palencia)* of which he was director. He did not measure the animal faeces outside of the barn i.e. when working on fields or pasturing; so he measured the potential available manure that could be collected and applied onto croplands.

Despite his accuracy, these numbers could not be generalised for the province. He warned here and there in his text that, unlike the farms of the area, his livestock was well fed and housed at night all year long. Yet, his data is especially useful because he gives the production per live weight, thus allowing us to adapt the coefficients to the average sizes of each province. The productions of manure that another well-known agronomist, Jose María de Soroa, describes in his "*Prontuario del agricultor y del ganadero"* (Soroa 1953) were based on these coefficients from Cascón (1918), so it seems a good starting point.

Table 5.15.Daily coefficients of manure (beds included) production and bedding material

	Manure ($kg \cdot day^{-1} \cdot kg$ live weight^{-1})	Bedding material (kg bed$\cdot$kg manure^{-1})
horse	17.7	0.18
cow	18.3	0.22
sheep	27.7	0.16
swine	27.0	0.24

Source: Cascón (1918)[12].

These coefficients, applied to the available live weights for Catalonia:

Table 5.16. Daily manure (beds included) production ($kg \cdot day^{-1} \cdot head^{-1}$) of every livestock type in Catalonia, based on weights of the four provinces.

	($kg \cdot day^{-1} \cdot head^{-1}$)
Cows and oxen	20.1
Horses	17.0
Mules	15.0
Donkeys	11.1
Sheep	3.3
Goats	2.9
Swine	5.7

Source: Cascón (1918) and (JCA 1920)[13].

[12]Cascón (1918)presented his results twice in his book, one disaggregated (p. 107-110) and the other aggregated (p. 69-70). Although both are of the same order of magnitude, using the disaggregated value we did not get the same value that he presents as aggregated. Therefore, we assumed that he made an operation error and hence we used his disaggregated values.

As mentioned, manure production depends on diet and livestock type, which were far from standardised at the province level. In addition, as one would expect, the amounts of bedding materials had great variability too. The numbers that Cascón (1918) provided are probably the most accurate Spanish source for the beginning of the twentieth century. Moreover, they represent the best practices at the time, which were not common. As he stated when referring to other farms of the province of Palencia: "*las condiciones son tan diferentes en la casi totalidad de las fincas, que habría necesidad de reducir estas cifras lo menos en un 90 por 100*" (Cascón 1918: 68). In Palencia, the lower influence of the sea strengthens the continental climate. Moreover, its landscape together with the composition of livestock numbers was different from the ones of our studied provinces, except for the plain of Lleida. Notwithstanding the common practices of farmers, which vary locally. This is why we thought that applying his 90% difference as a rule of thumb could be too much for our case studies.

However, what is manure? Moreover, what is *fresh* manure? Actually, "manure" is an ambiguous product; it is the result of a certain degree of fermentation of animal excrements mixed up with certain amount of other materials. The degree of fermentation is, when described, imprecise: mature, medium decomposed, re-decomposed, good manure, fresh, etc. are some of the words that agronomists from who we took the information used to describe manure; and water content is not always specified. Those "other materials" could be straw and whatever vegetable products coming from cropland or from uncultivated land, but could also be waste from industries, e.g. tannery, or even faeces from other species (humans included) as well. Everything was allowed in the manure heap, and practices varied from farmer to farmer.

All this was happening at such a disaggregated level that it was impossible to cover it within the provincial or regional scope. Manure was the key point of the balance so whatever affecting significantly manure would affect significantly the balance. At this point, we asked ourselves if it was useful to use only the measurements that one author made at his farm, even though he was the best of his time. Hence, to capture the potential variability, we averaged the production of manure from other authors of the time (see Marco et al. (forthcoming)). The values estimated from Cascón (1918) are between those ranges (Table 5.17).

[13]We used the coefficients of horses, for mules and donkeys; and the coefficient of sheep, for goats.

Table 5.17. Averages of manure production of each livestock type

Livestock type	Manure (kg·day^{-1}·head^{-1})
Cows and oxen	27.4±7.3
Horses	20.1±4.9
Mules	17.3±3.7
Donkeys	8.9±2.4
Sheep	1.9±1.1
Goats	1.6±1.1
Swine	7.0±2.8

Sources: Cascón (1918) and JCA (1920) corrected; references included in Marco et al. (forthcoming): Aguilera 1906; JCA 1892; Loomis, Connor, and Cassman 2011; Van Slyke 1932.

The total amount of manure potentially applied to the cropland of each region is in Table 5.18. According to agronomists of the time, the required amount of semi-decomposed manure applied to soils should be between 5-6 t·ha^{-1}; or 6-7.2 t·ha^{-1} of fresh manure (Llorente and Galán 1910). Only Old Catalonia had been able to apply this amount of manure.

The differences among regions were the consequence of the livestock numbers. The disequilibrium between a plain with low livestock numbers together with big cropland area and the Pyrenees with higher livestock densities and less cropland area than pastures was already known: "[...]*mientras en la zona pirenaica, esencialmente ganadera, el cultivo ocupa poca extensión, en el resto de la provincia aumenta éste siendo menor el numero de cabezas de ganado. De esto se deduce que la producción de estiércol es insuficiente para las necesidades del cultivo, aumentando el deficit las malas prácticas que se emplean en su preparación y conservación, y el descuido o completo abandono en que se tiene hasta el momento de incorporarle al terreno*." (JCA 1921: 380).

Table 5.18. Estimation of the potential amount of manure (beds+excrements) applied to cropland area

	Manure (t·ha^{-1})
Old Catalonia	7.04±0.82
New Catalonia	2.15±0.13
Pyrenees	5.22±0.84

. Source: JCA (1923), MF (1924) and explanations in text.

4.3. Bedding material

As far as we know, beds were made mostly from straw, although other materials could have been used. To estimate whether the coefficients of Cascón (1918) were pertinent to our case, we looked for the straw from cereals and leguminous crops produced at the province level (JCA 1923). Some of the quantities reported produced a straw/grain ratio too low or too high. Therefore, we corrected these ratios before calculating the total production of straw showed in Table 5.19.

Table 5.19. Bedding material required compared to the straws produced

	Straws required ($kt \cdot y^{-1}$)[a]	Straws produced ($kt \cdot y^{-1}$)[b]	Straws required reduced a 40% ($kt \cdot y^{-1}$)[a]
Barcelona	203±32	157	101±16
Girona	306±52	156	152±26
Lleida	251±37	278	125±19
Tarragona	60±14	203	30±7

Source: [a]our own calculation from Cascón (1918) and [b] JCA (1923).

The impossibility, except for the case of Tarragona, to follow the coefficients proposed by Cascón (1918) drove us to conclude that his numbers were only possible at experimental level. Maybe he was not so misguided when he said that the amounts of manure that could be collected in the other farms were 90% less. He stated in his book that it was common to use insufficient bedding material or even not use it at all: "*se observa la falta de camas en todos los locales donde se albergan los ganados; la no renovación de las mismas* […]*la mayor parte de los ganados, sobre todo los de renta, duermen en cobertizos, durante el tiempo frío, sin más cama que el terrizo desigual de los mismos, por cuyo abandono se pierden la mayor parte de las deyecciones líquidas de los animales, con perjuicios para los mismos, por las emanaciones continuas, y en cuanto a las sólidas, quedan también en condiciones de aprovecharse lo menos posible*." (Cascón 1918: 52).

Nevertheless, he pointed out that it was not a matter of straw scarcity but a lack of the habit to use it whenever it was available: "*en los años de abundante cosecha, la paja sobrante, que no ha encontrado mercado, se abandona en el campo en grandes montones para que se pudra a fuerza de tiempo y de la acción de los agentes atmosféricos, especialmente del agua, con unas pérdidas en peso que no bajarán seguramente de los 2/3 del peso inicial. Esta paja debiera aprovecharse* *para camas y en el momento en que estuviera empapada por los orines del ganado conducirla al estercolero, con lo que se mejoraría el estiércol producido y se reducirían al mínimum las pérdidas en peso*.” (Cascón 1918: 54-55).

As it was impossible to know straw use data at provincial level, we built an approximation by modifying the coefficients from Cascón (1918), which is the only reliable source that we have. We allowed for the trade of straw between provinces—although we did not have data to reallocate the surplus of straw from one province to the other. It is needless to say that straw was not only used for animal bedding, but by reducing by 40% the coefficients from Cascón (1918) the average consumption of straws by province results in less than100 % (Table 5.19).

We obtained the chemical composition of the straws produced in each province (see Table 5.20) by using the coefficients of Soroa (1953).

Table 5.20. Nutrient composition of all straws produced within the provinces in 1922

	N (%)	P (%)	K(%)
Barcelona	0.70	0.11	0.80
Girona	0.55	0.13	0.82
Lleida	0.56	0.11	0.75
Tarragona	0.55	0.11	0.66

Source: JCA(1923) and Soroa (1953).

4.4. Nutrient composition of manure

We found in the literature an extended list of compositions more or less complete that could match the livestock type of the time, thus lengthening the one from Lana-Berasain (2010) (Annex 2.B). We found historical data of manure composition averages for all livestock types mixed, and some information for manure composition per livestock type, only a few were specified e.g. calves, work oxen, breeding piglets, milk cows, etc. We selected the composition of manure per livestock type and discarded the values that were too high or too low, and as above, calculated the averages (Table 5.21).

The highest variability was of cow and oxen, which is not a surprise if we take into account the various specialisations (work, milk or meat) which is higher than other livestock types. In addition, specialisation involves very different diets, which was already occurring in the first decades of the twentieth century in Spain

(JCA, 1920: 475). This caused higher standard deviations in the Pyrenees due to the high number of cattle in pastures (see Annex 2. C). The average for all livestock types together were coherent with the ones that Gotaas (1956) reported as average for stable manure at fresh state: 70-80% moisture, 0.3-1.9% N, 0.1-0.6% P_2O_5 and 0.3-1.2% of K_2O. Also with those adopted by Gallego (1986) 0.62%N, 0.27% P_2O_5 and 0.63% of K_2O.

Table 5.21. Average values of nutrient composition of manure

Average manure type	N (% fresh weight)	P (% fresh weight)	K (% fresh weight)	Water (%)
Cows and oxen	0.60±0.25	0.13±0.06	0.53±0.43	72.91±14.00
Horses and other from horse family	0.60±0.05	0.12±0.01	0.46±0.12	70.25±7.09
Sheep and goat	0.89±0.18	0.16±0.08	0.46±0.10	64.33±4.04
Swine	0.52±0.08	0.15±0.05	0.38±0.10	80.17±5.78

Source: see Annex 2.B.

5. Non-manure but organic nutrient sources

5.1. Rainfall or deposition

To analyse this, we followed the guidelines of Garcia-Ruiz et al. (2012) and looked for values from an area of lowpollution. Probably, the best known sampling site known to ecology scientists for this in Catalonia is La Castanya. La Castanya valley (altitude 700 m a.s.l.), central to the Montseny massif, is a topographically sheltered position from the polluted air masses from the Barcelona conurbation, and removed from local pollution sources."(Rodà et al., 2002: 206). From 1983 to 1999 these authors measured a yearly wet deposition of 5.67 kg $N{\cdot}ha^{-1}$ ($N\text{-}NO_3^-$ and $N\text{-}NH_4^-$ of 2.71 and 2.96 respectively), with an average yearly precipitation of 929 mm. They considered these values as moderate, so although La Castanya is sheltered topographically and relatively far from direct influence of cropland or roads, it still receives some anthropogenic influence in the form of N deposition. The total deposition was 14.8 kg $N{\cdot}ha^{-1}$ after dry deposition was added, which is a value that can have adverse effects in Mediterranean type ecosystems (Rodà 2002; Avila et al. 2009). Rodrigo (1998) measured wet deposition of $N\text{-}NO_3^-$, $N\text{-}NH_4^-$, $P\text{-}PO_4^{3-}$ and K^+ as 27.9 (±2.3), 31.9 (±3.4), 1.03 (±0.12) and 3.45 (±0.42) µeq/L during the year (1995-1996); with a precipitation of 1275 mm (Rodrigo 1998: 60), the values per ha were the following:

Table 5.22. Deposition values for La Castanya base

	$N\text{-}NO_3^-$ ($kg\cdot ha^{-1}$)	$N\text{-}NH_4^-$ ($kg\cdot ha^{-1}$)	$P\text{-}PO_4^{3-}$ ($kg\cdot ha^{-1}$)	K^+($kg\cdot ha^{-1}$)
La Castanya	4.71	5.34	0.246	1.70

Source: Rodrigo (1998: 129-132).

The groundof La Castanya is located in a place with an exceptional high annual precipitation compared to the average of the provinces (see Table 5.23). Garcia-Ruiz et al. (2012) estimated N, P and K depositions of 3.48, 0.61 and 3.0 $kg\cdot ha^{-1}$ respectively for an area with an annual rainfall average of 640 mm, like Barcelona province. Therefore, we corrected the values from La Castanya by the precipitation averages of each province see (Table 5.23). Values of N were still higher than the ones of Garcia-Ruiz et al. (2012), whereas P and K were lower. We found even lower values in Holland et al. (1999), who attribute pre-industrial N deposition levels of 0.43 $kg\cdot ha^{-1}\cdot y^{-1}$ (0.07-0.60) and 0.67 $kg\cdot ha^{-1}\cdot y^{-1}$ (0.19-1.12) to Mediterranean scrubland and xenomorphic forest/woodland respectively. These latter were the values used in the previous chapter (Tello et al. 2012). However, Holland et al. (1999) did not take into account pre-industrial cropland areas but potential natural vegetation only, which could explain why their values are so low. Lacking other criteria, we used data from Table 5.23.

Table 5.23. Average wet deposition corrected by precipitation averages (1921-2000)

	$N\text{-}NO_3^-$ ($kg\cdot ha^{-1}$)	$N\text{-}NH_4^-$ ($kg\cdot ha^{-1}$)	$P\text{-}PO_4^{3-}$ ($kg\cdot ha^{-1}$)	K^+ ($kg\cdot ha^{-1}$)	Precipitation Average (1971-2000) (mm)
Barcelona	2.36	2.68	0.12	0.86	640
Girona	2.68	3.03	0.14	0.98	724
Lleida	1.36	1.54	0.07	0.50	369
Tarragona	1.86	2.11	0.10	0.68	504
Huesca(Pyrenees)	1.98	2.24	0.10	0.72	535

Source: Rodrigo (1998) and Agencia Estatal de Meteorología en España (2014).

5.2. Free fixation

Following the Broadbalk experiment in Rothamsted in United Kingdom (Rothamsted Research 2006), Goulding (1990) suggested that N free fixation could have a range of 5-10 $kg\cdot ha^{-1}$. Berry et al. (2003) used the lowest value of this range to calculate the N, P and K budget values in nine organic farms in United Kingdom. However, (Loomis et al. 2011) suggested a lower range of 1-5 $kg \cdot ha^{-1}$ because bacteria need anaerobial conditions, which in turn requires wet conditions and this is not the case in our area. As a matter of fact, Tello et al. (2012) and Garcia-Ruiz et al. (2012) used values between this range: 4 $kg \cdot ha^{-1}$ or even less according to tillage intensity for his study case in the South of the Iberian Peninsula.

5.3. Irrigation

Similarly, Garcia-Ruiz et al. (2012) stated that contributions of nutrients dissolved in water for irrigation could be approximated by concentrations in current unpolluted streams nearby the case study site. Lacking data of unpolluted streams, we collected a 10-year average data set from fountains in unpolluted areas of each province from the ACA[14] online database (Table 5.24). The values were similar to those considered in Garcia-Ruiz et al. (2012) 2.0, 0.05 and 2.0 mg of N, P and $K \cdot L^{-1}$. The highest values were for Tarragona, but as it is located at the end of the Ebro River basin, and is the second longest river of the Iberian Peninsula, average values higher than the other provinces could be acceptable.

We assumed that intensities of water use by crop type would match on average, with those reported in "*Medios que se utilizan para sumministrar el riego a las tierras y distribución de los cultivos de la zona regable*"(JCA1916). This report quantifies irrigation at province level per hectare of crop type. At that time, irrigation, with the exception of horticultural land, was only "support" irrigation. Water inputs were the minimum doses just to avoid the failure of the crop, e.g. irrigated wheat was watered twice along all the crop´s lifespan (JCA 1916). In Figure 5.6,5.7 and Annex 2.C, we applied the irrigation doses to the cropland areas described in 1922 (JCA 1923). Barcelona however, had such high values due to the large area of horticultural land.

[14]*AgènciaCatalana de l'Aigua*, is a public entity considered the hydraulic authority in Catalonia.

Table 5.24. Ten year average data from fountains in unpolluted areas of each Catalan province

Province	N ($mg \cdot L^{-1}$)	P ($mg \cdot L^{-1}$)	K ($mg \cdot L^{-1}$)
Barcelona	2.96	0.04	2.01
Girona	2.07	0.09	1.05
Lleida	1.32	0.03	0.83
Tarragona	4.41	0.03	3.06

Averages from ACA website. http://aca-web.gencat.cat/sdim/visor.do [last accessed April 2013]

5.4. Symbiotic fixation

Atmospheric N is fixed via symbiotic association between leguminous plant roots and bacteria from the Rhizobium genus. According to Loomis et al. (2011): "There are a range of methods, some ingenious but none entirely satisfactory, for determining the amounts of N fixed by legume crops", therefore it is a matter of choosing a method, and we used the one provided by Garcia-Ruiz et al. (2012). It uses the share of the plant N content which corresponds to N fixed (aerial parts and roots); the share of the total plant N content that corresponds to the roots and the share of the total plant N fixed that is settled into the soil (rhizodeposition). As our case study could be considered mostly belonging to Mediterranean climate we used 60, 38 and 18 % respectively (Garcia-Ruiz et al. 2012), which is to multiply by 1.14 the N content of the productions of leguminous crops from JCA (1923).

The results were reasonable, as they ranged between 98.2-163.6 $kg \cdot ha^{-1}$ for the four provinces, which are between the most common ranges of symbiotic fixation observed (Loomis et al. 2011). This procedure was particularly useful to us, because we only had aerial biomass production data (grain plus straws or fresh forage depending on the crop). In the balance (Figure 5.6, 5.7 and Annex 2.C) we took into account the flow of total N fixed, and once the aerial parts harvested was subtracted, the N fixed that remained in soil were those of roots and rhizodeposition.

Growing leguminous plants in order to bury them when they are flowering (so they do not create grain) has been widely practiced in Mediterranean climates and is commonly known as 'green manure'. Although this practice can have an effect in the mobilisation of other soil nutrients, we only took into account the net gain of nitrogen. Beyond fertilisation, green manure has positive effects on the biological activity in soils, as well as the control of weeds and plagues (Guzmán and Alonso 2008). Green manure crops are grown between crop rotations or between the rows of trees on plantations. In the Mediterranean they used to be planted in fall and harvested in spring (Guzmán and Alonso 2008).

Although there were leguminous crops planted in 1922, it is not clarified whether they were used as green manure. Moreover, it is probable that the area corresponding to green manure would have been hidden by summer cereal productions, fallow land or simply not reported in JCA (1923). However, the engineers of JCA (1921) estimated the area devoted to green manure, which differed from one province to the other (see Table 5.25).

Table 5.25. Estimated area of green manure

	Total cropland (ha) [a]	Green manure area (ha) [b]	Green manure area (% of cropland)	Yield as in [b] (t/ha)	Yield corrected (t/ha)
Barcelona	219,038	4,000	1.83	4.00	12.95
Girona	132,075	10,000	7.57	10.90	10.90
Lleida	498,556	650	0.13	15.00	15.00
Tarragona	289,357	540	0.19	0.03	12.95

Source: a JCA (1923); b JCA (1921).

As said above, green manure is cut before the plant grains and buried into the soil. As it never goes out from the fields, it is very difficult to find averages of the production and composition of the aerial part cut and buried. According to qualitative descriptions (JCA 1921), any leguminous plant could be used as green manure, but we do not know them quantitatively. As shown in Table 5.25, only the yields described for Girona and Lleida were between the ranges of other leguminous crops harvested as fresh forage. Therefore we used the produce average of these two provinces to estimate the yields for the other two provinces. According to Soroa (1953) the N content in the fresh aerial part of leguminous crops is between 4.3 and 7.8 $g \cdot kg^{-1}$ so we used the average of 6.1 $g \cdot kg^{-1}$ for all provinces.

5.5. *Humanure*[15]

A number of sources recognise the use of human faeces at some degree of composting from human settlements where cesspits were used for disposal of human faeces. This was a common situation in Catalan villages, even for cities like Barcelona that were waiting for the renewal of their sewage system as proposed by García-Faria (1893). When discussing the awareness of farmers in replenishing nutrients from the soil, Cascón (1918), from his experimental farm in Palencia, praises the Catalan farmers because there were known to use human faeces as fertiliser. JCA (1921) quantifies the night soils used in Catalonia and gives details about how cesspits from Barcelona were emptied and then how human faeces were treated and transported to be sold to the farmers of the coastal horticultural land surrounding Barcelona to cultivate vegetables that were eventually sold to Barcelona. This kind of nutrients recirculation from city to fields has been also reported by several other cases, also at the beginning of the twentieth century (Ellis and Wang 1997; Kimura et al. 2004; Billen et al. 2007a; Billen et al. 2007b; Kimura and Hatano 2007). It even was recommended by engineers at the beginning of the twentieth century such as King (1911) and the Spanish García-Faria (1893).

Pedro García Faria was an engineer and hygienist of the Spanish state during the end of the nineteenth and twentieth century. In 1893 he finished the "*Proyecto del subsuelo de Barcelona, Alcantarillado-Drenaje-Residuos urbanos*" (García-Faria 1893). Beyond designing a new sewage system and an urban residues collection system, he collected data of the dead for a period of ten years, sorting them by neighbourhoods and illnesses. With this data he wanted to justify the urgent reforms that the sewage system of Barcelona city needed. He resolved the final disposal of humanure by dumping it in fields next to the agricultural lands of the Llobregat River delta, on the outskirts of the city. His objective was to make a controlled compost process and use the organic matter as fertiliser (García-Faria 1893). Although his project was approved in 1891, the City Council fired him and his team in 1895 due to pressures from a large company that wanted to take over the project (Miranda 2006). The execution of the project was delayed until 1901, thus starting the long and intricate history of the construction of the modern sewage system of the city of Barcelona during the twentieth century (Theros 2012), but García-Faria never worked again on it. Although his project was never

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[15]We prefer to use this elegant way of referring to human fecal material and urine and its potential as fertiliser(Jenkins 2005) as started to be used in scientific journals e.g. Schneider and McMichael (2010) instead of a large and confusing list of euphemisms.

executed completely, his report has constituted a well-known source of information of the city of Barcelona at the end of the nineteenth century.

As we do not have exact numbers, we made a proxy based on the way human faeces were disposed, which were mainly four: rivers or sea—thus losing all potential fertiliser—, cesspits—where mainly the solids were collected—, tanks and manure heaps —both allowing the collection of solids and liquids. The first two were related to urban areas or villages, tanks to buildings with annexed gardens that in urban areas could often be monasteries, hospitals, etc. The last one was mostly related to more isolated rural settlements, usually with livestock such as the *masies*. Hence, there is a relation between the disposal system and the type of human settlement. In the first half of the twentieth century in Catalonia there were broadly three: disseminated rural houses or group of houses (populations that inhabit a 10 buildings or less are accounted as 'disseminated' by Nomenclator), concentrated rural villages and urban areas (Esteve-Palós 2003).

Therefore, to estimate the humanure available in agriculture, we associated the potential collection of faeces through three disposal systems typical of each settlement type. Disseminated rural settlements used manure heaps, concentrated rural villagers used cesspits that were emptied from time to time by farmers or sealed and urban populations had a mixture of cesspits and insufficient sewage systems which released human waste directly to water bodies. We ignored equating the tanks as that would have involved too much detail for the scale we were considering.

The report from García-Faria (1893), quantifies Manchester´s waste flows as one third going into the river, one third released by the sewage system to fields and one third collected, treated and sold. As our biggest urban area is Barcelona city, we assumed two thirds were released into the sea and one third stored in cesspits and then potentially collected. To differentiate between rural and urban we followed the criteria of the Spanish *Instituto Nacional de Estadística*, which considers as urban settlements with a population higher than 2000 inhabitants. We did not account for urine due to the difficulties in collecting it and the high losses due to ammonia volatilisation.

Once accepted these assumptions, the difficulties were the same as for animal manure. Production of human faeces is between 135-270 $g \cdot day^{-1} \cdot cap^{-1}$ fresh weight without urine (Gotaas 1956). Authors at the time gave chemical compositions of humanure, which as manure, used to be human faeces with certain but unknown degree of fermentation while more modern authors give average compositions of fresh human faeces, all of them are summarized in Appendix B, and the average is in Table 5.27. As animal manure, it contributed the same N losses calculated in section 3.4. However the estimations of quantities described for Girona and Lleida in JCA (1921) seemed too high to be credible if they were without urine (Table 5.26). A recurrent problem when trying to collect statistical information about the application of human faeces is the ambiguity in naming them. The agronomists in charge of the statistics used to refer to them equally as *abonos flamencos, letrinas* or *fenta*, thus omitting the specific forms of preparation of (usually commercial) human faeces. For instance, the *abonos flamencos* were a liquid fertiliser resultant from the fermentation of liquid and solid human faeces, whereas *fenta or poudrette* was the result of drying only the solid part (Llorente and Galán 1910). We then decided to use our calculations instead of those in the JCA (1921).

Table 5.26. Human faeces (fresh weight without urine) potentially collected

Province	Consumption of humanure[a] (t)	Average Potentially human faeces collected [b] (t)
Barcelona	?	37,827±12270
Girona	90,000	11,330±3114
Lleida	97,240	10,523±3288
Tarragona	6,560	11,418±3197

Source: [a] JCA (1921) and [b] Gotaas (1956).

Table 5.27. Chemical composition of humanure found in literature

	N (%)	P (%)	K (%)	Water (%)
Average	1.02±0.66	0.28±0.26	0.32±0.21	75±8

Source: see Annex 2.B.

5.6. Seeds

Seeds are a mix of genetic material and reserves to feed the seedlings. So, these reserves could be considered as nutrients recycled and were very important in pre-industrial systems (Chorley 1981). For all cereals, legumes and potatoes sown by splitting the tuber, we used the quantities per ha and composition described in Soroa (1953).

5.7. Other

Other sources of fertilisers were waste from leather industry, garbage from villages and towns, pomaces from oil and wine elaboration, *hormigueros* and buried biomass from forest or scrubland. The report from JCA (1921) gives quantitative information for some of the other fertilisers (Table 5.28).

A big share of garbage from towns and villages, «*barreduras*», used to end up in fields directly, as a component of manure heaps or abandoned in piles on the outskirts and eventually used as fertiliser. In the report of JCA (1921) garbage data for Barcelona and Lleida are lacking. Although (García-Faria 1893) estimates that the production of garbage for the city of Barcelona was the same as in Paris i.e. 1 $L \cdot cap^{-1} \cdot day^{-1}$, the heterogeneity and the uncertainty of the production of garbage makes it difficult to make an estimation. Additionally, at the beginning of the twentieth century in Barcelona, there were both organised and illegal—«*canbuscaires*»—collectors of garbage. They competed for organic garbage in order to feed mainly swine and some poultry that were breed in the city for self-consumption or the selling of meat and manure. Therefore, the organic garbage collected remained within the city. This practice was banned in 1960 due to swine fever (CLD 2014).

All these uncertainties, together with the fact that these kind of fertilisers correspond to a minor share in comparison with the ones described previously, we considered it reasonable to use the source as it is. Our only concern was around the use of oil and winery pomaces reported in JCA (1921), as the provinces with the highest productions did not seem to use it as fertiliser and Girona apparently uses more wine pomaces than it produces as described in JCA (1923). The former could be explained because the preferences for pomace uses other than using it as a fertiliser: was to feed livestock or to make olive pomace oil and distillates from oil and winery pomaces respectively. The excess of Girona is nonsense when compared to values reported in literature for similar processes (Daneo 1921; Cabrera 1995). Consequently we adjusted the value to the one reported in JCA (1923).

Although in section 3.2 we calculated prunings, we did not followed their path in returning to fields by burial either fresh or burnt. Piling pruning from vines or other trees, covering them with soil and burning it, was the fertilising practice called «*hormiguero*». It was traditionally used in clearances for shifting agriculture, but it was also used for permanent crops (Miret 2004). This practice was documented in some parts of Catalonia at least until 1960 andcould have been widespread in the arid areas of Catalonia at the end of the nineteenth century (Saguer and Garrabou 1995b).Unfortunately, we do not have quantitative information about the areas of application. While in our main reference for fertilising methods, JCA (1921), they are barely mentioned. Merely documented as the destiny of the straws of maize in Lleida and through the spread of ashes from bushes (gorse (*Ulex parviflorus*) and mastic (*Pistacia lentiscus*)), in the coastal areas of Tarragona.

In the opinion of agronomists of the time, they were substituted by synthetic fertilisers, as to fertilise with *hormiguero* required lots of fuel (bushes, vine shoots, etc.) and human labour (Mestre and Mestres 1949). However, the practice could have been abandoned before. Relating to its fertilising properties, all the N was lost by the combustion, but after the fire collapsed there was an increase of P and K in soils (Olarieta et al. 2011). Hence, the effect of not accounting for them in the balance would be to underestimate the potential returns (when the origin was pruning) or additions (when the origin was forest or scrubland) of P and K.

Table 5.28. Other fertiliser materials

Province	Fertilisertype	Total amount (t)
Barcelona	Waste from leather industries	1400
Girona	Winery pomace (orujos)	56000
Girona	Proposed winery pomace	9030
Girona	Garbage	15300
Lleida	Sugar industry residues	1600
Tarragona	garbage	1500
Tarragona	Winery pomace (orujos)	900
Tarragona	Oil pomace (alpechín)	20
Tarragona	poultry	7
Tarragona	pigeon	4

Source: JCA (1921), for the NPK composition, see Annex 2.B.

6. Synthetic fertilisers

Regular statistics for synthetic and mineral fertilisers did not start until 1928 (Gallego 1986), but for 1919 we can use the already mentioned exceptional report of JCA (1921). Gallego (1986) distinguished five different dynamics of the Spanish consumption of synthetic fertilisers until the Civil War (1936-39). Our period of study coincides with the end of the unavailability of fertilisers due to

World War I and the beginning of a consumption trend that recovered and surpassed the levels before the war.

The main kinds of synthetic fertiliser consumed where superphosphates, then nitrogenous and potash was not important. The Spanish exploitation of potash did not start until 1925, but even then, almost all was exported. This trend was followed by Catalonia, where P was the dominant synthetic fertiliser during the same period (Saguer and Garrabou 1995b). The low use of synthetic fertilisers in Girona compared to the rest has been explained by Pujol(1998) as being the result of the great availability or organic fertilisers. At the same time, the areas of highest consumptions were near industrial centres or those provided with irrigation facilities. This explains that Barcelona was at the head of the consumption in Catalonia.

Table 5.29. Average of compositions of the main synthetic fertilisers.

Fertiliser's name	Content of N (%)	Content of P_2O_5 (%)	Content of K_2O (%)
Potassium nitrate	13.1±0.7		44.2±1.3
Calcium nitrate	14.0±1.8		
Sodium nitrate (Chile saltpeter)	15.5±0.4		
Ammonium sulfate	20.4±0.4		
Potassium chloride			51.8±1.8
Kainite			13.3±2.5
Potassium sulfate			49.7±0.5
Superphosphate		18.0±1.6	
Slag of iron ores (*Escorias Thomas*)		16.4±5.0	

Source: Aguirre-Andrés(1971) in Gallego (1986); García-Luzón (1922); López-Mateo (1922); Soroa (1953).

Fraud in the composition of synthetic and mineral fertilisers was rather common in Spain at the beginning of the twentieth century. To counter it the Spanish government started to legislate in 1900, but still it was known that buying synthetic fertilisers outside agrarian unions or associations was to be exposed to fraud (Sanz 2005). This situation made them fall into disrepute among farmers (García-Luzón 1922). In spite of these facts and due to lack of data, we did not take into account the differences of richness between adulterate or pure forms of synthetic fertilisers. The composition of pure forms can be found in a series of authors (García-Luzón 1922; López-Mateo 1922; Soroa 1953), unsurprisingly matching among them and with the composition that Gallego (1986) uses in his article, which as its turns out uses data from Aguirre-Andrés(1971) (see Table 5.29).

As a matter of clarification, although some of the agronomists distinguish between ordinary superphosphates (OSP) (aprox. 20%) and triple superphosphate (TSP) (aprox. 50%), the statistical data refers to the broad category of Superphosphateonly. As we cannot assign a weight, the average of all chemical composition reported for Superphosphate would show a misleading deviation, so we adopted the more conservative value and used the values of ordinary superphosphates.

7. Results and discussion

The data to build the nutrient balance c.1920 were mainly aggregated at province level. However, we found it useful to aggregate them according to historical and geo-climatic patterns distinguishing three regions—Old, New Catalonia and the Pyrenees. Our main concern was to split the province of Lleida into the areas mainly influenced by the plains—becoming part of New Catalonia— and the areas mainly influenced by the Pyrenees mountains.

Although classification into the three main regions was a useful interpretation, some interesting differences among provinces remained hidden within the aggregation (Table 5.30). Pyrenees was the less densely populated area and the area with the highest share of forest, scrubland and pastures. Vineyards have an important role in Barcelona and Tarragona provinces, increasing the share of land occupied by permanent covers, while the plains of Lleida´s annual crops and fallow land were more important than elsewhere in Catalonia. Finally, a very distinctive feature of Girona was the high livestock densities per cropland area. At higher precipitation, the settlement pattern structured in *masies* and the Eastern Pyrenees—the Pyrenees go on through to the North of Girona descending in altitude until their end in the Mediterranean Sea—allowed the coincidence of a relatively small area of summer and winter pastures (Vilà-Valentí 1973).

Table 5.30. Summary of some characteristics of the provinces studied c.1920

	Old Catalonia		Pyrenees	New Catalonia	
	Barcelona	Girona	Lleida Pyrenees	Lleida Plain	Tarragona
Rainfall (mm)[a]	640	724	535	369	504
Population density (inhab/km^2)[b]	176	56	12	47	55
Cropland density (ha/inhab) [cb]	0.16	0.41	1.43	1.57	0.81
% forest, scrubland and pastures over total area[c]	56.9	68.1	79.9	21.9	44.7
Ratio forest, scrubland and pastures over annual crops[16c]	3.5	3.2	4.9	0.4	4.1
Ratio permanent land covers over annual crops[c]	4.9	3.5	5.0	0.9	7.4
Livestock density per cropland area(LU 500 kg/km^2) [dc]	40	85	57	13	9

Sources: a Agencia Estatal de Meteorología en España (2014); b Instituto Nacional de Estadística (1920);c JCA (1923); d JCA (1920) and MF (1924).

In section 2 we provided some hints to interpret the results of the nutrient balance. First, there was probably an accumulated deficit, at least in some areas, so in this case a positive balance did not mean pollution challenges. Secondly, we could not disaggregate data per crop type, but we knew that there were underfertilised crop types, so we cannot conclude strongly that a regional equilibrium means that everything was balanced simply that the physical means to do it were available.

The balance per cropland area of the three regions (Figure 5.6) shows the main features described above. Old Catalonia and the Pyrenees compensated for the extractions unlike New Catalonia, where the lack of manure increased the relative importance of other sources of fertility, such as N deposition through rainfall and free fixation. This means that, although it is uncertain if maintaining fallow land was effective for this purpose, its existence could have obeyed fertility logic[17].

[16]Although questionable, we refer to herbaceous crops and annual crops indistinctly when we want to group all the crops that were not wooden and perennial.

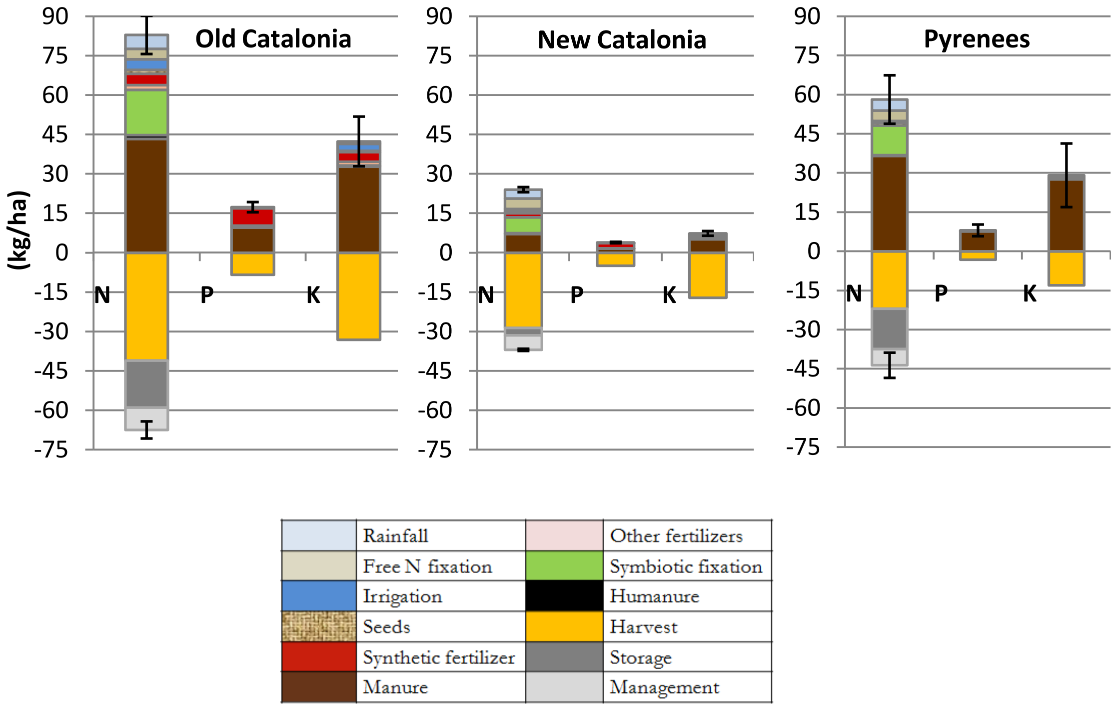
[17]The effectivity of fallow storaging water in arid climates with summer drought requires careful analysis of rainfall probabilities and soil water-storage capacity together with the presence of crop residues (Loomis et al. 2011). However,there are other additional reasons that could justify the existence of land temporally unsown, thesewere,the accumulation of available N due to natural inputs and other nutrients due to mineralisation,the elimination of weeds and plagues andthe

This effect was more pronounced in Lleida province, where fallow land was approximately 30% of cropland, and less important in Old Catalonia as the fallow land there was almost nonexistent (Table 5.1). Note that this affected the interpretation in Figure 5.6 as harvest are extractions per total cropland area, but not yields, because fallow was included in cropland area.

As we said in section 5.3, although the largest number of irrigated land was situated in New Catalonia, it was only 'support irrigation'. Hence, the highest inputs from irrigation are found in Old Catalonia due to its large area of horticultural land, which was heavily irrigated.

While the N storage losses were applied only to manure and humanure and could be almost half of their content in N, the management losses included the losses due to the application of each fertiliser and tillage of cropland.

Figure 5.6. Nutrient balances (kg·ha^{-1}) per cropland area (sown and fallow) in the three regions of Catalonia



Negative values represent extractions and losses, positive values are additions of nutrients. The N losses due to storage and management of soils calculated in section 3.4 are represented as grey columns following the harvest-yellow column. Error bars are the accumulation of Standard

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scarcity of human labour.Whatever it may be, those areas with less rainfall were those with larger areas of fallow land at the end of nineteenthcentury (Saguer and Garrabou 1995b).

Deviations in each extraction or addition bars and are due to the estimation of manure, humanure and the N emissions associated. See Annex 2.C for more details.

The coexistence of organic and industrial fertilising strategies seems to have been successful in Old Catalonia. Nevertheless, two different scenarios occurred in each of its provinces. While the synthetic fertilisers were used almost exclusively in Barcelona, Girona barely made use of them and had enough manure to balance the cropland extractions. Thus we agree with Pujol (1998) that the non use of synthetic fertilisers in Girona province was not a matter of concern for soil fertility. Interestingly, extractions from horticultural land were important due to high yields—as two or three harvests could be obtained per year— in spite of the small share of horticultural land (Figure 5.3). The belt of horticultural land surrounding the city of Barcelona was already important circa 1920. Actually, all sources indicated that they were fertilised with almost everything that farmers could get. Comprehensively they were the destination of the night soils from the city.

While in the region of the Pyrenees there was a huge availability of nutrients from manure in comparison to what was extracted, most of them would go to pastures and not to cropland. However, we have not enough data to specify if croplands in the Pyrenees were receiving enough manure or not.In comparison, New Catalonia presents a very different picture, as the additions of nutrients barely could balance the extractions. This is consistent with Gonzalez de Molina (2002) as sustaining the limits necessary to keep or increase fertility by organic means were stricter in arid climates.

The scale of this balance of nutrients is regional, therefore a general equilibrium does not necessarily mean that all crop types were balanced. The opposite could be true, that the cash crops circa 1920 were carefully fertilised. Such was the case of rice, oranges and hazelnuts in the best endowed lands (Calatayud 2006; Garrabou 2006), thus creating a soil mining trap in the rest of cropland areas. Even if we had took into account the *hormigueros*, the K deficit had persisted: the sum of K content in all pruning is not enough to cover the 30% deficit. We know that a maintained deficit undermines the capacity of soils to increase yields and thus the capacity of the territory to sustain people. However, one of the limitations of this work is that it covers one time slot, so we lackedquantitative information about the persistency of negative balances.

It is known that after a long period of underfertilisation yields used to drop until they stagnated. This trend was demonstrated with experiments of the Broadwalk plots in Rothamsted station (UK), which stabilised at 900 $kg{\cdot}ha^{-1}$ after 50 years of unmanured continuous wheat cropping (Shiel 2010). Also with the experiments of Sanborn (Missouri), where the wheat yielded 600 kg·ha^{-1} after 30 years of non manuring (Shiel 2010). Similarly, after 80 years without fertilisation, a rye field in Germany reached an equilibrium near 900 kg·ha^{-1}(Loomis et al. 2011).

Hence, the average of non-irrigated wheat yields in a period of 37 years could be useful as a reference trend (Table 5.31). The highest yields were from Old Catalonia, and the lowest from Lleida (recall that we cannot split the yields between plain and Pyrenees), which is closest to the benchmark. However, some difficulties arise in the interpretation of these yields as aridity, not only fertility, strongly affected yields. Despite this, we grouped Lleida and Tarragona into the unit of New Catalonia, Tarragona had higher proportions of wooden crops. Then, the smaller area of cereals were mostly concentrated in the North-East of the Conca de Barberà and Alt Camp, an area where the annual rainfall, as a matter of exception in the province, is comparable to the cereal areas of Girona, so this provided higher yields than in Lleida than were expected.

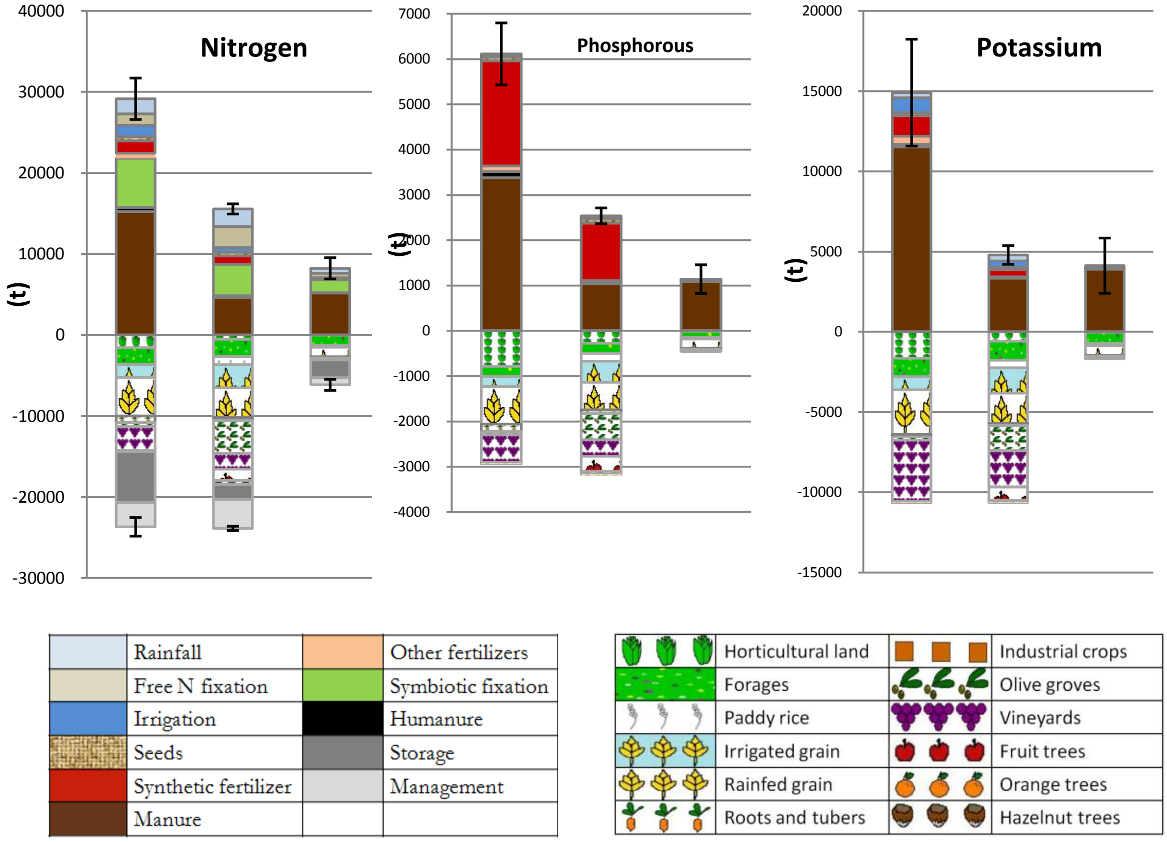
Table 5.31. Averages of non-irrigated wheat yields (kg·ha^{-1}) of the Catalan provinces (1898-1935).

Barcelona	Girona	Lleida	Tarragona
1376	1384	1049	1246

Source: GEHR(1991).

Recall that in section 2, we said that excess was not a matter of concern c. 1920. Nevertheless, surpluses and deficits of nutrients in both figures make us wonder about the rationality behind the amount of fertiliser applied. Were farmers calculating the nutrient balances of the lands they worked? All the fertility guides for farmers written by Spanish agronomists —which we consulted and cited above—recommended exact doses of fertiliser (manure, synthetic or whatever type) to return nutrients to soils. They gave data to estimate nutrient extractions and additions. However, their advice was always accompanied too by complaints about the underfertilisation of the Spanish soils. Therefore, it is hard and even ridiculous to believe that the common practice was to calculate soil nutrient budgets and act accordingly. Most likely, farmers were using what was physically, socially and economically available.

Figure 5.7. Nutrient balances (t) in the total cropland area (sown and fallow) per nutrient



In each figure, the first bar is Old Catalonia, second New Catalonia and third Pyrenees. Negative values represent extractions and losses, positive values are additions of nutrients. The N losses due to storage and management of soils calculated in section 3.4 are represented as grey columns following the harvest columns. Error bars are the accumulation of Standard Deviations in each extraction due to the estimation of manure, humanure and the N emissions associated. Note that each area is not necessarily at the same scale.

The relative importance of each type of fertiliser in the replenishment of the nutrients harvested depends on the nutrient (Figure 5.7). Manure was the main source to restock the K extracted in all regions. The organic non-manure sources were more important for N than for the other nutrients due to deposition and leguminous crops. They were even more important than manure in New Catalonia. Although in third place, synthetic N (mainly from Chilean nitrates) was also needed to close the balance in Barcelona province —as we said above the weight of synthetic fertilisers in Girona was almost null—and was important for the rice and orange fields of Tarragona. The most important source of P applied in New Catalonia and the province of Barcelona were synthetic fertilisers.

Hence, the list of social and economic factors influencing the availability of fertilisers seems endless. Just to mention some: the settlement type together with land property allowed or limited the existence of livestock, the rules of landowners allowed, forced or prohibited the cultivation of forages or green manure, the proximity to markets, the organization of cooperatives or unions—which spread the knowledge of using and facilitated buying synthetic fertilisers—, or the competition with other uses such as gunpowder and hence the influence of wars and conflicts.

Nevertheless, there was space for trial and error as well due to the immediate effects of synthetic fertilisers. For instance, in areas where N could be better balanced by organic means than P, a little addition of synthetic P could have been very cost-effective in the initial years thus generating the idea that "the more the better". However, if it was not well managed, the soluble forms of P fertiliser added to the soil can be transformed into insoluble compounds immobilising P in soils (Smil 2000) appearing ineffective. Additions of N above the needs of the plant creates an increase in their total biomass but not in yields (Loomis et al. 2011). In addition, crop rotations make some nutrients less scarce in relative terms, and vineyards could have had a similar role, as they need less N and P than cereals thus giving the apparent image that there is no need for fertilisation.

8. Conclusion

The changing human-nature relations in agriculture during the Socio-Ecological Transition of industrialisation arise an exchange of nutrient flows in cropland. Although limited detailed information is available for Spain at the beginning of the twentieth century, our analysis reveals that using regional statistics entails comprehensive results. In general, when refering to administrative divisions, we include historical human settlements, geography and climate characteristics to define regions.

Since versatility is both the light and the shadow of building a nutrient balance, we explicitly followed existing peer reviewed guidelines from García-Ruiz et al. (2012). As an adaption to the availability of our data, we calculated the N losses though IPCC (2006), which are mainly dependent on the amount of fertilisers added, its storage and the management of soils. In fact, some of the suggestions of the agronomists of the time (Cascón 1918; De la Cruz-Lazaparán 1924) to diminish N deficits of the nutrients balance followed this same logic: to develop techniques to minimize N losses and hence enlarging N content of the fertilisers applied. Ironically, not pushed by scarcity but by the excess, these techniques are being implemented nowadays in a top-down strategy to avoid N pollution of groundwater or emissions to the atmosphere, as leaching of N to groundwater is occurring in the area (Penuelas et al. 2009).

Circa 1920 could be considered a period in between the two waves of the socio-ecological transition toward an industrial regime (González de Molina 2010). However, there were regional differences in the strategies to balance nutrients in cropland areas even in the North-East of the Iberian Peninsula. While Old Catalonia and the Pyrenees had available means to balance the nutrient flows, such was not the case in New Catalonia. This region relied on first wave strategies, i.e. playing with the relative scarcity of nutrients to keep harvesting without replenishing the nutrients in soils, thus bringing the system to unsustainable limits. This was done due to the fact that crops can still yield under relative scarcity of nutrients, concentrating fertilisers (synthetic as well) in some selected areas or cultivating crops that extracted relatively less nutrients than others such as vineyards. Nevertheless, although low yields can be maintained they cannot be enhanced. This makes the system more vulnerable to changes in the system such as population growth, scarcity of water, price failures.

About the other two regions, there were differences in the strategies followed to close the balances. Pyrenees and Girona province could still rely entirely on organic strategies. Some of them did not need human labour, others required from them, such as manure, humanure, green manure, seeds and others that still were important enough to appear in official statistics. Hence, the availability of these organic sources of fertility was not only relying on physical factors such as rain but in economic and social factors too. Lastly, perhaps the province of Barcelona was a paradigmatic example of the second wave since nutrient flows were balanced by combining all these organic strategies with the use of synthetic fertilisers.

If the disequilibrium in the balance of nutrient flows in cropland was an influenced on the crisis of organic agricultures, in drier areas as well as in certain crops (permanent wooden crops) fertility problems were exacerbated and hence the transition from the first wave to the second longer. Other areas could close the balance due to the mix of organic and synthetic fertilising methods. This means that although the second wave had not fully occurred within the region, and that the use of synthetic fertilisers was minimal compared to other countries, the coexistence of the two modes of metabolism could stabilise fertility, at least temporary.

Since methodological issues absorbed the most of this paper, we could go no further from the physical dimension of the nutrient balances. More than a limitation, we consider this as an invitation to other fields of study to connect social and economic factors with fertility.

True, the Catalans may have turned stones into bread. Not directly, but by growing vines in stony and sloping soils where lots of terraces were patiently built, and then by buying wheat with the money gained through wine exports. What is missed in the old adage is that, to do this, a high level of exploitation of labour and land was needed. Some historians have recognized that this viticultural labour entailed an exploitation of human beings by others which led to strong social unrest. Yet the soil mining through long-lasting land overexploitation still remains widely unknown. This chapter has tried to bring this issue to light.

Annex 2.A. Nutrient composition of crops considered

Table 2.A.1.Nutrient composition of crops according toSoroa(1953)

Crop name	***Latin name***	**Product type**	**N (g/kg fresh weight)**	**P (g/kg fresh weight)**	**K (g/kg fresh weight)**	**Source**
alfalfa	*Medicago sativa*	aerial part fresh	7.20	0.70	3.74	Soroa (1953)
alfalfa	*Medicago sativa*	hay	23.00	2.31	12.12	
algarroba	*Vicia articulata*	dry forrage	23.30	3.19	17.76	
algarroba	*Vicia articulata*	grain	40.20	4.02	9.63	
alforfón	*Fagopyrum esculentum*	hay	21.50	1.75	17.85	
altramuz	*Lupinus albus*	aerial part fresh	5.00	0.48	1.25	
altramuz	*Lupinus albus*	dry forrage	27.40	2.71	16.35	
altramuz	*Lupinus albus*	hay	27.40	2.53	6.64	
alverja	*Vicia sativa*	hay	22.80	2.71	17.43	
arveja	*Vicia sativa*	dry forrage	22.70	2.71	16.35	
avena	*Avena sativa*	aerial part fresh	3.70	0.57	4.65	
centeno	*Secale cereale*	aerial part fresh	5.30	1.05	5.23	
esparceta flor natural	*Onobrychis viciifolia*	hay	22.10	2.01	10.79	
esparceta. pipirigallo	*Onobrychis viciifolia*	aerial part fresh	5.10	0.65	4.32	
esparceta. pipirigallo	*Onobrychis viciifolia*	hay	18.80	2.93	11.37	

esparceta. pipirigallo	*Onobrychis viciifolia*	grain	36.90	4.02	9.13
lupulina	*Medicago lupulina*	aerial part fresh	7.80	0.52	3.32
lupulina	*Medicago lupulina*	hay	24.00	2.01	14.36
ornitopo o serradella	*Ornithopus compressus*	aerial part fresh	4.80	0.96	6.39
ornitopo o serradella	*Ornithopus compressus*	dry forrage	21.60	3.97	26.48
ornitopo o serradella	*Ornithopus compressus*	grain	34.90	3.41	6.81
pradera natural	unknown mixture	hay	14.30	2.01	15.02
sorgo	*Sorghum bicolor*	aerial part fresh	4.00	0.35	3.32
sulla	*Hedysarum coronarium*	dry forrage	10.30	1.22	3.82
sulla. zulla	*Hedysarum coronarium*	aerial part fresh	2.20	0.26	0.75
trebol blanco flor	*Trifolium repens*	aerial part fresh	5.70	0.87	2.74
trebol blanco flor	*Trifolium repens*	hay	23.20	3.41	10.87
trebol encarnado	*Trifolium pratense*	aerial part fresh	4.30	0.35	2.16
trebol encarnado	*Trifolium pratense*	hay	19.50	1.57	9.71
trebol pratense o violeta	*Trifolium pratense*	aerial part fresh	4.80	0.57	3.65
trebol pratense o violeta	*Trifolium pratense*	grain	30.50	6.33	11.21

trebol pratense o violeta	*Trifolium pratense*	hay	19.70	2.44	15.44
vallico o raygrass	*Lolium perenne*	aerial part fresh	5.50	0.96	5.81
vallico o raygrass	*Lolium perenne*	hay	16.30	2.71	16.77
algarrobo	*Ceratonia siliqua*	fruit	9.30	2.27	6.64
almond	*Prunus dulcis*	branches and leaves	0.60	0.70	0.83
almond	*Prunus dulcis*	fruit	38.20	9.34	11.37
bellota	*quercus*	fruit	4.00	0.65	5.15
castaña común	*Castanea sativa*	fruit	6.90	1.18	5.89
castaña indias	*Aesculus hippocastanum*	fruit	6.50	1.14	5.81
cerezo	*Prunus cerasus*	fruit	1.60	0.31	2.16
cerezo	*Prunus cerasus*	leaves	4.90	0.48	3.82
cerezo	*Prunus cerasus*	wood	2.40	0.22	1.00
ciruelo	*Prunus domestica*	fruit	1.30	0.22	1.58
ciruelo	*Prunus domestica*	leaves	7.20	0.74	7.14
ciruelo	*Prunus domestica*	wood	5.00	0.65	2.32
manzano	*Pyrus malus*	fruit	0.30	0.09	0.75
manzano	*Pyrus malus*	leaves	10.70	0.74	2.74
manzano	*Pyrus malus*	wood	4.50	0.52	1.91
melocotonero	*Prunus persica*	fruit	0.80	0.17	1.49
melocotonero	*Prunus persica*	leaves	9.10	0.57	4.81
melocotonero	*Prunus persica*	wood	4.30	0.44	1.74
membrillero	*Cydonia oblonga*	fruit	1.20	0.22	1.99
membrillero	*Cydonia oblonga*	leaves	8.60	0.79	3.57

membrillero	*Cydonia oblonga*	wood	4.90	0.70	3.40
morera	*Morus alba*	leaves	14.00	1.05	6.06
naranjo	*Citrus sinensis*	fruit	3.20	1.66	2.66
naranjo	*Citrus sinensis*	leaves	7.00	0.44	2.66
naranjo	*Citrus sinensis*	wood	7.00	1.88	4.81
peral	*Pyrus communis*	fruit	0.40	0.09	0.91
peral	*Pyrus communis*	leaves	7.00	0.52	3.49
peral	*Pyrus communis*	wood	2.90	0.48	2.32
almorta. alverjon. muela	*Lathyrus sativus*	grain	48.40	4.28	10.13
altramuz	*Lupinus albus*	grain	52.20	6.24	8.47
arroz	*Oryza sativa*	grain	13.50	2.01	1.66
arveja. veza	*Vicia sativa*	grain	44.00	4.32	6.64
avena	*Avena sativa*	chaff	6.40	0.57	3.74
avena	*Avena sativa*	grain	17.60	2.97	3.98
avena	*Avena sativa*	straw	5.60	1.22	13.53
cebada	*Hordeum vulgare*	chaff?	4.80	1.05	7.72
cebada	*Hordeum vulgare*	grain	15.50	2.53	2.66
cebada	*Hordeum vulgare*	straw	5.70	0.87	8.72
centeno	*Secale cereale*	chaff	5.80	2.44	4.32
centeno	*Secale cereale*	grain	17.60	3.71	4.81
centeno	*Secale cereale*	straw	5.60	1.22	9.71
garbanzo	*Cicer arietinum*	grain	31.60	4.10	11.12
guisante	*Pisum satibum*	grain	35.40	3.84	8.13
guisante	*Pisum satibum*	stalk and leaves	10.40	1.66	8.88
haba	*Vicia faba*	grain	40.60	5.06	9.96

haba	*Vicia faba*	straw	16.30	1.79	16.60
judia	*Phaseolus vulgaris*	grain	41.50	4.10	11.62
judia	*Phaseolus vulgaris*	straw	10.40	1.66	8.88
lenteja	*Lentils culinaris*	grain	38.10	2.27	6.39
lenteja	*Lentils culinaris*	straw	10.10	2.10	4.32
maiz	*Zea mays*	cob heart	2.30	0.09	1.91
maiz	*Zea mays*	grain	16.00	2.58	3.07
maiz	*Zea mays*	stalk and leaves	1.90	0.44	3.07
maiz	*Zea mays*	straw	5.20	2.18	12.12
mijo	*Panicum miliaceum*	grain	22.10	2.93	3.24
sarraceno o alforjon	*Fagopyrum esculentum*	aerial part fresh	3.90	0.35	3.15
sarraceno o alforjon	*Fagopyrum esculentum*	dry forrage	21.40	1.83	17.76
sarraceno o alforjon	*Fagopyrum esculentum*	grain	14.40	2.49	2.24
soja	*Glycine max*	grain	57.80	7.60	16.85
soja	*Glycine max*	straw	12.50	2.01	8.05
sorgo	*Sorghum bicolor*	grain		2.40	2.66
trigo	*Triticum*	chaff	7.20	1.75	6.97
trigo	*Triticum*	grain	20.80	3.45	4.32
trigo	*Triticum*	straw	4.80	0.96	5.23
ajo	*Allium sativum*	stalk and leaves	3.10	0.48	2.24
alcachofa	*Cynara scolymus*	flower		1.70	1.99
apio	*Apium graveolems*	stalk and leaves	2.40	0.96	6.31
calabaza	*cucurbita*	fruit	1.10	0.70	0.75

cebolla	*Allium cepa*	stalk and leaves	2.70	0.57	2.08
col	*Brassica oleracea*	stalk and leaves	2.40	3.23	5.23
coliflor	*Brassica oleracea var. botrytis*	stalk and leaves	4.00	0.70	2.99
esparrago	*Asparagus acutifolius*	sprout	2.40	0.35	2.24
esparrago	*Asparagus acutifolius*	stalk	1.70	0.26	1.16
espinaca	*Spinacia oleracea*	leaves	5.20	0.79	2.41
fresa	*Fragaria*	fruit	0.60	0.13	0.75
lechuga	*Lactuca sativa*	stalk and leaves	2.20	0.44	3.24
lombarda	*Brassica oleracea var. capitata f. rubra*	stalk and leaves	5.30	0.92	3.24
melon	*Cucumis melo*	fruit	1.80	1.09	1.08
pepino	*Cucumis sativus*	fruit	1.60	0.52	1.99
pimiento	*Capsicum annuum*	fruit	2.40	1.09	2.57
puerro	*Allium ampeloprasum var. porrum*	leaves	5.40	0.83	4.48
puerro	*Allium ampeloprasum var. porrum*	stalk	4.50	0.61	2.16
rabano	*Raphanus sativus*	root	1.90	0.22	1.33
sandia	*Citrullus lanatus*	fruit	1.20	0.44	1.66
tomate	*Solanum lycopersicum*	fruit	5.10	0.52	1.25
zanahoria	*Daucus carota*	grain		5.15	11.87
zanahoria	*Daucus carota*	leaves	5.10	0.44	2.41
zanahoria	*Daucus carota*	root	2.20	0.44	2.49
cacahuete	*Arachis hypogaea*	fruit	45.00	3.93	12.45
cañamo	*Cannavis sativa*	grain	26.10	7.38	7.80

cañamo	*Cannavis sativa*	stalk	14.80	1.00	3.82
colza	*Brassica napus*	aerial part fresh	4.60	0.52	2.91
colza	*Brassica napus*	grain	31.00	7.16	7.30
colza	*Brassica napus*	pod	8.50	1.57	4.73
colza	*Brassica napus*	straw	5.00	1.18	8.05
cotton	*Gossypium*	fiber	3.40	1.53	3.82
cotton	*Gossypium*	leaves	32.10	5.20	9.79
cotton	*Gossypium*	stalk	14.60	2.58	11.70
lino	*Linum usitatissimum*	fiber	4.80	1.88	8.30
lino	*Linum usitatissimum*	grain	32.00	5.68	8.63
tabaco	*Nicotiana tabacum*	leaves	25.70	2.14	33.62
tabaco	*Nicotiana tabacum*	stalk	17.20	4.37	23.16
olivo	*Olea europaea*	fruit	4.50	0.48	0.42
olivo	*Olea europaea*	leaves	10.00	1.00	4.65
olivo	*Olea europaea*	wood	7.50	1.27	3.24
batata o moniato	*Ipomoea batatas*	root	2.40	0.35	3.07
nabo	*Brassica napus*	leaves	4.20	0.48	2.16
nabo	*Brassica napus*	root	1.80	0.35	2.74
pastinaca. chirivia	*Pastinaca sativa*	root	5.20	0.87	4.48
pataca. topinambour	*Helianthus tuberosus*	root	3.20	0.61	3.90
pataca. topinambour	*Helianthus tuberosus*	stalk and leaves	5.30	0.39	2.57
patata	*Solanum tuberosum*	root	3.40	0.70	4.81
patata	*Solanum tuberosum*	stalk and leaves	4.90	0.70	3.57

remolacha azucarera	*Beta vulgaris L. subsp. vulgaris var. altissima*	grain	16.90	3.27	9.21	
remolacha azucarera	*Beta vulgaris L. subsp. vulgaris var. altissima*	leaves	3.00	0.31	3.32	
remolacha azucarera	*Beta vulgaris L. subsp. vulgaris var. altissima*	root	1.60	0.35	3.24	
remolacha forrajera	*Beta vulgaris*	grain	16.90	3.32	7.55	
remolacha forrajera	*Beta vulgaris*	leaves	3.00	0.44	3.74	
remolacha forrajera	*Beta vulgaris*	root	1.80	0.26	3.40	
vid	*Vitis vinifera*	fruit	1.70	0.65	4.15	
vid	*Vitis vinifera*	leaves	8.00	0.70	2.32	
vid	*Vitis vinifera*	wine	0.20	0.13	0.83	
vid	*Vitis vinifera*	wood	2.00	0.17	2.49	
vid	*Vitis vinifera*	winery pomace	10.00	1.31	4.15	Soroa (1953)
vid	*Vitis vinifera*	leaves	8.00	0.70	2.32	
vid	*Vitis vinifera*	pruning	2.00	0.17	2.49	

Table 2.A.2. Crops composition according to other modern sources.

Crop name	*Latin name*	Produce type	Water (g/100 g)	N (g/kg fresh weight)	P (g/kg fresh weight)	K (g/kg fresh weight)	Source
puerro	*Allium ampeloprasum var. porrum*	stalk	91	2.56	0.35	1.56	CESNID (2003)
cebolla	*Allium cepa*	root	86	1.86	0.33	1.57	Mataix (2003)
ajo	*Allium sativum*	root	67	9.12	1.34	4.46	CESNID (2003)
apio	*Apium graveolems*	leave	94	1.44	0.32	3.05	CESNID (2003)
esparrago	*Asparagus officinalis*	stalk	93	3.52	0.56	2.69	CESNID (2003)
avena	*Avena sativa*	straw	11	5.12	1.07	13.07	INRA et al. (n.d.)
avena	*Avena sativa*	grain	2	27.02	5.23	4.29	Mataix (2003)
avena	*Avena sativa*	aerial part fresh	74	4.56	0.61	7.00	INRA et al. (n.d.)
remolacha forrajera	*Beta vulgaris*	aerial part fresh	82	4.78	0.66	0.00	INRA et al. (n.d.)
remolacha forrajera	*Beta vulgaris*	root	84	1.75	0.33	0.00	INRA et al. (n.d.)
remolacha azucarera (root)	*Beta vulgaris L. subsp. vulgaris var. altissima*	molasses	24	17.32	0.23	38.76	INRA et al. (n.d.)
remolacha azucarera (root)	*Beta vulgaris L. subsp. vulgaris var. altissima*	root	81	2.35	0.43	2.86	INRA et al. (n.d.)
remolacha azucarera (leave)	*Beta vulgaris L. subsp. vulgaris var. altissima*	leaves and tops	89	3.26	0.22	0.00	INRA et al. (n.d.)
acelga	*Beta vulgaris var. cicla*	leave. stalk	90	3.20	0.43	3.78	Mataix (2003)
nabo forrajero	*Brassica napus*						
nabo	*Brassica napus*	root	89	1.28	0.34	2.40	Mataix (2003)
col	*Brassica oleracea*	leave	90	2.24	0.41	2.70	Mataix (2003)

repollo	*Brassica oleracea*	leave	90	2.24	0.41	2.70	Mataix (2003)
brecol	*Brassica oleracea italica*	flower	90	4.80	0.67	3.70	Mataix (2003)
coliflower	*Brassica oleracea var. botrytis*	flower	90	3.52	0.48	3.19	Mataix (2003)
cañamo (fibra)	*Cannavis sativa*						
cañamo	*Cannavis sativa*	grain	9	34.65	4.17	0.00	INRA et al. (n.d.)
pimiento	*Capsicum annuum*	fruit	92	1.44	0.25	2.10	Mataix (2003)
castaño	*Castanea sativa*	fruit	51	3.20	2.56	3.84	Mataix (2003)
algarrobo	*Ceratonia siliqua*	fruit	17	10.38	1.25	0.00	INRA et al. (n.d.)
algarrobo	*Ceratonia siliqua*	aerial part fresh	49	7.78	0.51	0.51	INRA et al. (n.d.)
garbanzo	*Cicer arietinum*	straw	9	8.30	1.46	0.00	INRA et al. (n.d.)
garbanzo	*Cicer arietinum*	grain	2	32.80	3.75	8.00	Mataix (2003)
garbanzo	*Cicer arietinum*	bran	10	22.39	2.69	0.00	INRA et al. (n.d.)
escarola	*Cichorum endivia*	leave	91	4.64	0.40	2.07	Mataix (2003)
sandia	*Citrullus lanatus*	aerial part fresh	86	4.48	0.64	6.02	INRA et al. (n.d.)
sandia	*Citrullus lanatus*	fruit	93	0.80	0.09	1.10	Mataix (2003)
mandarinero	*Citrus reticulata y otros*	fruit	86	1.28	0.17	1.85	Mataix (2003)
naranjo	*Citrus sinensis*	fruit	78	0.96	0.28	2.94	Mataix (2003)
limonero	*Citrus x limon*	fruit	87	1.12	0.16	1.49	Mataix (2003)
roldon	*Coriaria myrtifolia*						
avellano	*Corylus avellana*	fruit	6	22.56	3.00	7.30	Mataix (2003)
melon	*Cucumis melo*	aerial part fresh	86	6.14	0.95	7.95	INRA et al. (n.d.)
melon	*Cucumis melo*	fruit	88	1.41	0.17	3.09	Mataix (2003)
pepino	*Cucumis sativus*	fruit	96	1.12	0.23	1.50	CESNID (2003)
calabaza	*Cucurbita*	crop by-product	86	4.44	0.70	0.00	INRA et al. (n.d.)
calabaza	*Cucurbita*	fruit	89	1.92	0.30	4.50	CESNID (2003)
calabacin	*Cucurbita pepo*	fruit	95	2.88	0.31	2.30	CESNID (2003)
cardo	*Cynara cardunculus*	leave. stalk	93	1.28	0.23	4.00	CESNID (2003)

alcachofa	*Cynara scolymus*	aerial part fresh	86	3.89	0.48	0.00	INRA et al. (n.d.)
alcachofa	*Cynara scolymus*	aerial part ensiled	76	4.80	0.00	0.00	INRA et al. (n.d.)
alcachofa	*Cynara scolymus*	flower	86	5.23	0.90	3.70	Mataix (2003)
chufa	*Cyperus esculentus*	root	5	6.64	2.56	7.10	http://www.tigernuts.es
zanahoria	*Daucus carota*	root	87	1.44	0.16	2.86	Mataix (2003)
nispero	*Eriobotrya japonica*	fruit	86	1.12	0.23	2.49	CESNID (2003)
higuera	*Ficus carica*	leaves fresh	68	7.12	0.58	0.00	INRA et al. (n.d.)
higuera	*Ficus carica*	fruit	86	1.44	0.23	2.32	CESNID (2003)
fresa freson	*Fragaria*	fruit	88	1.12	0.26	1.50	Mataix (2003)
zulla	*Hedysarum coronarium*	aerial part fresh	88	2.85	0.17	0.00	INRA et al. (n.d.)
zulla	*Hedysarum coronarium*	pods	88	2.65	0.00	0.00	INRA et al. (n.d.)
zulla	*Hedysarum coronarium*	hay	12	19.62	0.26	0.00	INRA et al. (n.d.)
pataca tupinambo	*Helianthus tuberosus*	aerial part fresh	68	7.91	1.07	0.00	INRA et al. (n.d.)
pataca tupinambo	*Helianthus tuberosus*	root	78	2.63	0.71	5.04	INRA et al. (n.d.)
cebada	*Hordeum vulgare*	straw	10	5.50	0.72	7.42	INRA et al. (n.d.)
cebada	*Hordeum vulgare*	grain	11	16.96	3.80	5.60	Mataix (2003)
cebada	*Hordeum vulgare*	aerial part fresh	75	4.40	0.43	3.50	INRA et al. (n.d.)
cisca o cogon	*Imperata cylindrica*	aerial part fresh	68	3.32	0.45	3.73	INRA et al. (n.d.)
moniato	*Ipomoea batatas*	root	70	2.64	0.45	3.66	INRA et al. (n.d.)node/12681
moniato	*Ipomoea batatas*	aerial part dried	12	18.69	2.74	12.57	INRA et al. (n.d.)node/12808
moniato	*Ipomoea batatas*	aerial part fresh	87	3.43	0.38	3.24	INRA et al. (n.d.)
nogal	*Juglans regia*	fruit	6	22.40	3.04	9.03	Mataix (2003)
lechuga	*Lactuca sativa*	leave	93	2.40	0.30	2.40	Mataix (2003)
almorta	*Lathyrus sativus*	aerial part fresh	87	4.22	0.42	0.00	INRA et al. (n.d.)
almorta	*Lathyrus sativus*	hay	10	25.75	1.89	0.00	INRA et al. (n.d.)
almorta	*Lathyrus sativus*	grain	11	34.80	2.69	0.00	INRA et al. (n.d.)

lenteja	*Lens culinaris*	straw	8	11.96	1.29	10.61	INRA et al. (n.d.)
lenteja	*Lens culinaris*	grain	8	36.80	4.00	11.60	Mataix (2003)
altramuz	*Lupinus albus*	straw	8	8.24	0.00	0.00	Lopez et al. 2005
altramuz	*Lupinus albus*	aerial part fresh	80	6.95	0.53	5.27	INRA et al. (n.d.)node/12269
altramuz	*Lupinus albus*	grain	11	53.28	1.78	0.00	INRA et al. (n.d.)
alfalfa	*Medicago sátiva*	silage	69	9.41	0.92	9.89	INRA et al. (n.d.)
alfalfa	*Medicago sátiva*	hay	11	26.03	2.32	21.99	INRA et al. (n.d.)
alfalfa	*Medicago sátiva*	aerial part fresh	80	6.56	0.50	4.46	INRA et al. (n.d.)
tranquillón	*mezcla de trigo y centeno*			0.00	0.00	0.00	
olivo (aceituna verde)	*Olea europaea*	fruit	78	2.08	0.17	0.91	Mataix (2003)
olivo (aceituna negra)	*Olea europaea*	fruit	56	3.20	0.24	0.40	Mataix (2003)
olivo	*Olea europaea*	oil cake crude with stones	12	10.94	0.70	4.47	INRA et al. (n.d.)
olivo	*Olea europaea*	oil cake exhausted with stones	12	17.96	0.97	8.04	INRA et al. (n.d.)
olivo	*Olea europaea*	oil cake crude without stones	13	13.30	1.14	9.19	INRA et al. (n.d.)
olivo	*Olea europaea*	oil cake exhausted without stones	17	14.57	1.82	11.92	INRA et al. (n.d.)
olivo	*Olea europaea*	olive oil pulp crude	22	14.56	1.17	0.00	INRA et al. (n.d.)
olivo	*Olea europaea*	olive oil pulp exhausted	11	17.60	1.42	0.00	INRA et al. (n.d.)
olivo	*Olea europaea*	olive kernel exhausted	7	47.62	0.00	0.00	INRA et al. (n.d.)
olivo	*Olea europaea*	olive pits exhausted	11	1.71	0.00	0.00	INRA et al. (n.d.)
olivo	*Olea europaea*	leaves fresh	50	7.86	0.45	0.00	INRA et al. (n.d.)

olivo	*Olea europaea*	skins	11	18.84	0.00	0.00	INRA et al. (n.d.)
olivo	*Olea europaea*	olive oil vegetation water	49	4.71	0.00	0.00	INRA et al. (n.d.)
olivo	*Olea europaea*	leaves and branches dried	10	11.21	0.99	0.00	INRA et al. (n.d.)
olivo	*Olea europaea*	aceite	0	0.00	0.00	0.00	CESNID (2003)
olivo	*Olea europaea*	ramon	28	10.46	0.00	0.00	SIA (n.d.)
esparceta	*Onobrychis viciifolia*	aerial part fresh	78	6.03	1.03	3.28	INRA et al. (n.d.)
esparceta	*Onobrychis viciifolia*	silage	69	7.26	0.68	0.00	INRA et al. (n.d.)
pipirigallo	*Onobrychis viciifolia*	hay	10	21.82	2.78	0.00	INRA et al. (n.d.)
arroz	*Oryza sativa*	straw dried	7	6.24	0.84	16.70	INRA et al. (n.d.)
arroz	*Oryza sativa*	grain	11	10.88	1.02	0.98	CESNID (2003)
arroz	*Oryza sativa*	aerial part fresh	65	5.70	0.55	5.54	INRA et al. (n.d.)
mijo	*Panicum miliaceum*	aerial part fresh	41	13.18	0.13		SIA (n.d.)
mijo	*Panicum miliaceum*	straw	6	5.59	0.47	0.00	INRA et al. (n.d.)
perejil	*Petroselinum crispum*	aerial part fresh	88	4.75	0.58	5.54	USDA (n.d.)
judía	*Phaseolus vulgaris*	grain and pods	89	3.04	0.38	2.43	Mataix (2003)
judía	*Phaseolus vulgaris*	crop byproduct dry	10	21.72	2.16	0.00	INRA et al. (n.d.)
judía	*Phaseolus vulgaris*	grain	8	34.24	4.00	11.60	Mataix (2003)
judía	*Phaseolus vulgaris*	straw	12	10.00	0.97	20.68	INRA et al. (n.d.)
piñon	*Pinus pinea*	fruit	9	22.40	7.10	6.43	Mataix (2003)
guisante	*Pisum satibum*	straw	11	11.65	0.98	13.94	INRA et al. (n.d.)
guisante	*Pisum satibum*	grain	1	34.56	3.30	9.90	Mataix (2003)
guisante	*Pisum satibum*	aerial part fresh	84	4.42	0.61	0.00	INRA et al. (n.d.)
albaricoque	*Prunus armeniaca*	fruit	86	1.28	0.24	2.90	Mataix (2003)
cerezo	*Prunus cerasus*	fruit	82	1.28	0.21	2.60	Mataix (2003)
cirolero	*Prunus domestica*	fruit	82	1.28	0.29	2.36	CESNID (2003)
almendro	*Prunus dulcis*	fruit	6	32.00	5.10	6.90	Mataix (2003)

melocotonero	*Prunus persica*	fruit	86	0.96	0.22	1.60	Mataix (2003)
nectarino	*Prunus persica*	fruit	86	1.44	0.18	2.12	CESNID (2003)
granado	*Punica granada*	fruit	78	2.67	0.36	2.36	USDA (n.d.)
peral	*Pyrus communis*	fruit	85	0.80	0.18	2.50	Mataix (2003)
manzano rojo	*Pyrus malus*	fruit	85	0.48	0.09	0.99	Mataix (2003)
rabano	*Raphanus sativus*	root	95	0.96	0.18	2.43	CESNID (2003)
zumaque	*Rhus coriaria*	grain	10	3.74	1.11	7.17	Musa and Haciseferogullari (2004))
zarzamora	*Rubus ulmifolius*	fruit	85	1.60	0.30	2.00	CESNID (2003)
mimbre	*Salix*	leaves	69	9.76	1.26	0.00	USDA (n.d.)
centeno	*Secale cereale*	aerial part fresh	83	4.06	0.00	0.00	INRA et al. (n.d.)
centeno	*Secale cereale*	straw	8	6.04	1.20	11.22	INRA et al. (n.d.)
centeno	*Secale cereale*	grain	8	14.11	3.74	2.64	Mataix (2003)
tomate	*Solanum lycopersicum*	fruit	92	1.60	0.27	2.50	Mataix (2003)
berenjena	*Solanum melongena*	fruit	93	1.98	0.21	2.62	Mataix (2003)
patata	*Solanum tuberosum*	aerial part fresh	77	4.01	0.00	0.00	INRA et al. (n.d.)
patata	*Solanum tuberosum*	aerial part ensiled	75	5.12	0.00	0.00	INRA et al. (n.d.)
patata	*Solanum tuberosum*	peel fresh	82	3.73	0.46	4.97	INRA et al. (n.d.)
patata	*Solanum tuberosum*	root	77	4.00	0.50	5.70	Mataix (2003)
sorgo	*Sorghum bicolor*	grain	13	15.10	2.88	3.76	INRA et al. (n.d.)
sorgo	*Sorghum bicolor*	hay	10	10.80	1.53	14.04	INRA et al. (n.d.)
sorgo	*Sorghum bicolor*	straw	7	5.51	0.65	12.00	INRA et al. (n.d.)
sorgo	*Sorghum bicolor*	bran and milling offal	10	16.81	4.40	5.03	INRA et al. (n.d.)
sorgo	*Sorghum bicolor*	aerial part sillage	72	3.04	0.85	5.79	INRA et al. (n.d.)
espinaca	*Spinacia oleracea*	leave. stalk	91	4.64	0.52	5.29	(CESNID (2003)
trébol rojo	*Trifolium pratense*	silage	73	8.42	0.64	0.00	INRA et al. (n.d.)

trébol rojo	*Trifolium pratense*	aerial part fresh	80	6.08	0.68	5.39	INRA et al. (n.d.)
trébol rojo	*Trifolium pratense*	hay	10	26.53	8.11	0.00	INRA et al. (n.d.)
trébol blanco	*Trifolium repens*	aerial part fresh	82	7.05	0.59	0.00	INRA et al. (n.d.)
trébol blanco	*Trifolium repens*	hay	17	30.04	0.00	0.00	INRA et al. (n.d.)
fenigrec	*Trigonella foenum-graecum*	aerial part fresh	69	8.23	0.68	0.00	INRA et al. (n.d.)
fenigrec	*Trigonella foenum-graecum*	hay	18	13.17	0.00	0.00	INRA et al. (n.d.)
trigo	*triticum*	straw	9	6.12	0.64	10.10	INRA et al. (n.d.)
trigo	*triticum*	hay	0	8.64	0.00	0.00	INRA et al. (n.d.)
trigo	*triticum*	grain	17	18.77	3.44	4.21	Mataix (2003)
enea	*Typha spp.*	aerial part fresh	93	1.02	0.24	1.67	USDA (n.d.)
algarroba	*Vicia articulata*	straw	8	15.16	0.00	0.00	López et al. (2005)
yero	*Vicia ervilia*	straw	8	14.13	0.00	0.00	López et al. (2005)
haba	*Vicia faba*	grain	9	41.76	5.90	10.90	Mataix (2003)
alverjon	*Vicia narbonensis*	pods	9	39.43	3.53	10.69	INRA et al. (n.d.)
alverjon	*Vicia narbonensis*	aerial part fresh	85	5.16	0.53	0.00	INRA et al. (n.d.)
alverjon	*Vicia narbonensis*	straw	9	10.53	1.01	15.63	INRA et al. (n.d.)
veza	*Vicia sativa*	aerial part fresh	81	7.10	0.85	0.00	INRA et al. (n.d.)
veza	*Vicia sativa*	hay	10	28.40	2.61	23.52	INRA et al. (n.d.)
veza	*Vicia sativa*	straw	8	10.32	1.20	0.00	INRA et al. (n.d.)
veza	*Vicia sativa*	grain	12	39.94	4.22	0.00	INRA et al. (n.d.)
uva blanca	*Vitis vinifera*	fruit	81	0.96	0.22	2.50	Mataix (2003)
uva negra	*Vitis vinifera*	fruit	81	0.96	0.16	3.20	Mataix (2003)
uva	*Vitis vinifera*	leaves and branches fresh	43	5.10	1.08	1.71	INRA et al. (n.d.)
uva	*Vitis vinifera*	marc dehidrated	8	20.52	2.84	7.42	INRA et al. (n.d.)
uva	*Vitis vinifera*	grape pomace including. seeds. stalks and skins	59	7.60	0.00	0.00	INRA et al. (n.d.)

uva	*Vitis vinifera*	fresh pruning	41	5.47	0.14	0.00	SIA (n.d.)
maiz	*Zea mays*	straw dried	7	5.50	0.65	12.63	INRA et al. (n.d.)
maiz	*Zea mays*	grain	17	13.66	2.56	3.30	Mataix (2003)

Annex 2.B. N P K composition of manures found in literature.

Table 2.B. N P K composition of manures found in literature

	N (%)	$P-P_2O_5$ (%)	$K-K_2O$ (%)	Water (%)	Source
Manure	0.4	0.09	0.50		López-Mateo (1922)
Manure	0.62	0.12	0.52		Domínguez-Vivancos (1978:408) in Gallego (1986)
Manure average	0.5	0.12	0.44		Soroa (1953:116)
Manure consumed	0.5	0.11	0.44	75	Nagore (1933) in Lana-Berasain (2010)
Manure fresh	0.39	0.08	0.37	75	Nagore (1933) in Lana-Berasain (2010)
Manure from farm	0.4	0.10	0.43		Soroa (1929)
Manure from farm	0.4	0.07	0.36	80	Abela (1880:81) in Lana-Berasain (2010)
Manure from farm	0.6	0.24	0.58		Uranga (1930) in Lana-Berasain (2010)
Manure from farm fresh	0.4	0.20	0.44		Soroa (1953:88)
Manure from farm mature	0.5	0.23	0.46		Soroa (1953:88)
Manure from farm max.	0.5	0.13	0.42		Navarro-de-Palencia (1921)
Manure from farm min.	0.4	0.09	0.33		Navarro-de-Palencia (1921)
Manure from farm twicedecomposed (*repodrido*)	0.6	0.22	0.46		Soroa (1953:88)
Manure from farm with human excrements	0.47	0.17	0.46	60	Cascón (1918:29)
Manure fully decomposed	1.5	0.38	1.17	53	De la Cruz-Lazaparán (1924)
Manure good	0.8	0.26	0.66		García de los Salmones (1915) in Lana-Berasain (2010)
Manure medium	0.47	0.13	0.43		García de los Salmones (1915) in Lana-Berasain (2010)
Manure medium decomposed	0.58	0.13	0.42		Cascón (1918:64)
Manure medium decomposed	0.62	0.22	0.54	71.7	De la Cruz-Lazaparán (1924)
Manure medium decomposed	0.5	0.12	0.36		JCA (1920:394)
Manure poor	0.3	0.09	0.25		García de los Salmones (1915) in Lana-Berasain (2010)

Manure very consumed	0.58	0.13	0.42	79	Nagore (1933) in Lana-Berasain (2010)
Manure with fern	0.92	0.17	0.61	63	García de los Salmones (1915) in Lana-Berasain (2010)
Manure with straw	0.81	0.18	0.30	54	García de los Salmones (1915) in Lana-Berasain (2010)
Calb 6 months	1	0.24	1.66	54	Nagore (1933) in Lana-Berasain (2010)
Cows and oxen	0.34	0.06	0.29		Soroa (1953:89)
Cows and oxen	0.5	0.11	0.42		González de Molina and Guzmán (2006:469)
Cows and oxen	0.4	0.09	0.08	85	Van Slyke (1932) in Tisdale and Nelson (1956:235)
Cows and oxen	0.34	0.07	0.33	78	Nagore (1933) in Lana-Berasain (2010)
Cows and oxen	0.55	0.10	0.50	80	Teuscher and Adler (1965:314) in Lana-Berasain (2010)
Cows and oxen	0.7	0.26	0.66	68	Domínguez Vivancos (1984:184)in Lana-Berasain (2010)
Cows and oxen	1	0.222	0.112	80	Gotaas (1956:37)
Cows and oxen for meat mature without beds	1	0.6	1.9	48	Loomis et al. (2011:222)
Cows and oxen fermented	0.41	0.09	0.42		Cavadini (1906:36) in Lana-Berasain (2010)
Cows and oxen for meat	0.59	0.16	0.36	85	Loomis et al. (2011:222)
Cows and oxen for meat mature with beds	1.1	0.8	2.2	50	Loomis et al. (2011:222)
Cows and oxen for milk fresh	0.52	0.11	0.34	86	Loomis et al. (2011:222)
Cows and oxen for milk mature without beds	0.5	0.2	0.8	82	Loomis et al. (2011:222)
Cows and oxen fresh	0.81	0.17	1.20	56	Nagore (1933) in Lana-Berasain (2010)
Cows and oxen fresh	0.3	0.08	0.33		Cavadini (1906:36) in Lana-Berasain (2010)
Cows and oxen housede	2	0.57	1.66	0	Domínguez Vivancos (1984:184) in Lana-Berasain (2010)
Donkey	0.6	0.13	0.50		González de Molina and Guzmán (2006:469)
Horse	0.58	0.12	0.44		Soroa (1953:88)
Horse	0.6	0.13	0.50		González de Molina and Guzmán (2006:469)
Horse	0.55	0.13	0.33	75	Van Slyke (1932) in Tisdale and Nelson (1956:235)

Horse	0.58	0.12	0.44	71	Nagore (1933) in Lana-Berasain (2010)
Horse	0.57	0.14	0.29	75	Gotass (1956:37)
Horse	0.7	0.11	0.62	60	Teuscher and Adler (1965:314) in Lana-Berasain (2010)
Horse dry matter	1.7	0.79	1.49	0	Domínguez Vivancos (1984:184) in Lana-Berasain (2010)
Horse medium fermented	0.6	0.10	0.58		Cavadini (1906:36) in Lana-Berasain (2010)
Mule	0.6	0.13	0.50		Gonzalez de Molina and Guzman (2006:469)
Pigeon	5	0.87	1.25		Soroa (1929)
Pigeon	4.5	0.92	0.83		Soroa (1953:89)
Pigeon	2.73	1.20	1.29	52	Gotaas (1956:37)
Pigeon	1.76	0.78	0.85		Cascón (1918:66)
Poultry	3	0.87	1.25		Soroa (1929)
Poultry	1.6	0.68	0.66		Soroa (1953:89)
Poultry	1	0.35	0.33	55	Van Slyke (1932) in Tisdale and Nelson (1956:235)
Poultry	1.5	0.44	0.33	10	Teuscher and Adler (1965:314) in Lana-Berasain (2010)
Poultry	2.7588	1.14	1.19	56	Gotaas (1956:37)
Poultry	1.5	0.70	0.75	72	Domínguez Vivancos (1984:184) in Lana-Berasain (2010)
Poultry broiler	1.29	0.35	0.34	75	Loomis et al. (2011:222)
Poultry mature without beds	1.6	2.1	2.8	55	Loomis et al. (2011:222)
Goat	0.83	0.10	0.56		González de Molina and Guzmán (2006:469)
Goat	0.45	0.13	0.75	70	Teuscher and Adler (1965:314) in Lana-Berasain (2010)
Sheep	0.83	0.10	0.56		Soroa (1953:89)
Sheep	0.83	0.10	0.56		González de Molina and Guzmán (2006:469)
Sheep	0.75	0.22	0.37	60	Van Slyke (1932) in Tisdale and Nelson (1956:235)
Sheep	0.83	0.10	0.50	65	Nagore (1933) in Lana-Berasain (2010)
Sheep	1.4	0.22	1.00	65	Domínguez Vivancos (1984:184) in Lana-Berasain (2010)
Sheep	1.2	0.26	0.33	68	Gotaas (1956:37)
Sheep	1.45	0.22	0.11	65	Teuscher and Adler (1965:314) in Lana-Berasain (2010)
Swine	0.45	0.09	0.50		Soroa (1953:89)
Swine	0.45	0.17	0.42		González de Molina and Guzmán (2006:469)
Swine	0.55	0.22	0.33	80	Van Slyke (1932) in Tisdale and Nelson (1956:235)

Swine	0.7	0.09	0.91		Cavadini (1906:36)
Swine	0.45	0.08	0.50	72	Nagore (1933) in Lana-Berasain (2010)
Swine	0.5	0.15	0.33	85	Teuscher and Adler (1965:314) in Lana-Berasain (2010)
Swine	0.5	0.13	0.42	75	Domínguez Vivancos (1984:184) in Lana-Berasain (2010)
Swine	0.68	0.15	0.19		Gotaas (1956:37)
Swine	0.62	0.21	0.34	87	Loomis et al. (2011:222)
Swine slurry	0.1	0.00	0.33		Cavadini (1906: 36) in Lana-Berasain (2010)
Swine slurry	0.2	0.02	0.25	92	Domínguez Vivancos (1984: 184) in Lana-Berasain (2010)
Swine slurry	1.5	0.04	4.07		Soroa (1953)
Swine slurry mature	1.6	0.5	0.8	82	Loomis et al. (2011)
Dust	0.05	0.04	0.13		Cavadini (1906: 36) in Lana-Berasain (2010)
Abono flamenco	0.43	0.09	0.20		Soroa (1953)
Poudrette	0.89	0.30	0.17		JCA (1920)
Abono flamenco	0.70	0.13	0.25		Cavadini (1906: 36) in Lana-Berasain (2010)
Human faeces MW (min)	1.00	0.26	0.17	80	Gotaas (1956: 35)
Human faeces MW (max)	2.31	0.78	0.68	66	Gotaas (1956: 35)
Human faeces MW	0.82	0.10	0.46	80	Yadav et al. (2010: 52)
Espumas de azucareria	0.3	0.35	0.25		Soroa (1953: 88)
Espumas de azucareria	0.8	0.65	0.25		Soroa (1953: 88)
Espumas de azucarería max	0.44	0.80	0.00		García-Luzón (1922)
Espumas de azucarería avg	0.62	0.73	0.12		García-Luzón (1922)
Espumas de azucarería min	0.23	0.45	0.00		García-Luzón (1922)
pulpa de remolacha agotada	0.44	0.07	0.48		Soroa (1953)
Garbage (Barreduras)from Castilian Villages	0.45	0.08	0.17	97,2	Cascón (1918)
Garbage (barreduras)	0.2	0.13	0.58		Soroa (1921)
Garbage	0.65	0.25	0.34	34	García de los Salmones (1915) in Lana-

(barreduras) of Pamplona					Berasain (2010)
Garbage (barreduras) urban	0.4	0.18	0.33		Soroa (1953)
Garbage fermented	0.68	0.41	0.48		García Faria (1893)
Garbage in villages	0.4	0.09	0.66	10	Gotaas (1956)
Garbage in villages	0.8	0.22	1.25	60	Gotaas (1956)
Guano muestra 1	0.56	5.64	0.12		García-Luzón (1922)
Guano muestra 2	3.95	4.78	0.21		García-Luzón (1922)
Orujo de aceituna	0.8	0.04	0.00		Soroa (1953)
Orujo de aceituna	1	0.11	0.66		Soroa (1921)
Orujo de aceituna	1.3	0.11	0.66		López-Mateo (1922)
Orujo de uva	1	0.11	0.21		Soroa (1921)
Orujo de vinificación	0.7	0.09	0.83		Soroa (1953)

Note: We multiplied P_2O_5 and K_2O by 0.4366 and 0.83 respectively to get P and K. Some of the sources did not specificity water content, as was explained in the text. To deal with this uncertainty and due to we wanted to use the old sources, we decided to use them as if they were in moisture weight. On the contrary, those sources that explicitly gave data in dry weight were transformed into moisture weight.

Annex 2.C. N, P, K balances per region

Table 2.C.1.NPK balance Old Catalonia

	N (kg/ha)	P (kg/ha)	K (kg/ha)
Manure	43.36±7.24	9.60±1.87	32.79±9.47
Rainfall(atmospheric deposition)	5.29	0.13	0.91
Free N fixation	4.00		
Irrigation	4.01	0.07	2.65
Symbiothic fixation	17.25		
Humanure	1.43±0.62	0.39±0.11	0.45±0.20
Seeds	1.49	0.23	0.51
Other fertilisers	1.80	0.35	1.43
Syntetic fertilizer	4.33±0.11	6.61±0.52	3.66±0.20
INPUT TOTAL	82.96±7.27	17.38±1,95	42.39±9.48
Agricultural produce	41.05	8.37	33.12
N losses due manure storage	17.90±3.25		
N losses due soil management	8.51±0.17		
OUTPUT TOTAL	67.45±3.26	11.79	33.12
Balance	15.51±7.97	5.59±1,95	9.27±9.48

Cropland area: 351,413 ha

Table 2.C.2. NPK balance New Catalonia

	N (kg/ha)	P (kg/ha)	K (kg/ha)
Manure	7.15±0.96	1.60±0.27	5.16±0.90
Rainfall(atmospheric deposition)	3.37	0.08	0.58
Free N fixation	4.00		
Symbiothic fixation	6.00		
Irrigation	0.89	0.01	0.58
Humanure	0.33±0.12	0.09±0.02	0.10±0.04
Seeds	0.73	0.15	0.24
Other fertilisers	0.04	0.02	0.02
Syntetic fertilizer	1.55±0.03	1.96±0.15	0.70±0.02
INPUT TOTAL	24.04±0.97	3.91±0.27	7.39±0.90
Agricultural produce	28.59	4.94	17.14
N losses due manure storage	2.83±0.42		
N losses due soil management	5.52±0.02		

OUTPUT TOTAL	36.94±0.42	5.38	17.14
Balance	-12.90±1.06	-1.47±0.31	-9.75±0.90

Cropland area: 646,693 ha

Table 2.C.3. NPK balance Pyrenees

	N (kg/ha)	P (kg/ha)	K (kg/ha)
Manure	36.57±9.28	7.67±2.24	27.60±12.19
Rainfall(atmospheric deposition)	4.22	0.10	0.72
Free N fixation	4.00		
Symbiothic fixation	11.37		
Irrigation	0.61	0.01	0.38
Humanure	0.28±0.16	0.07±0.03	0.09±0.05
Seeds	1.12	0.18	0.34
Other fertilisers	0.00	0.00	0.00
Syntetic fertilizer	0.00	0.00	0.00
INPUT TOTAL	58.16±9.28	8.04±2.24	29.13±12.19
Agricultural produce	21.98	3.21	13.02
N losses due manure storage	15.47±4.83		
N losses due soil management	6.19±0.25		
OUTPUT TOTAL	43.64±4.83	3.21	13.02
Balance	14.52±10.47	4.83±2.24	16.11±12.16

Cropland area: 141,220 ha

Note: The high accumulated error in the last column of the balance is the result of a subtraction. It just indicates the high sensitivity of the nutrient balance to the production and composition data concerning manure. Source: as described in text

Annex 2.D. Summary of sources used in the NPK balance for the regions of Catalonia c. 1920

Table 2.D. Summary of sources used in the NPK balance for the regions of Catalonia c. 1920

Extractions	Harvest	Produce	JCA(1923)	
		Pruning	(Marco et al.)	
		NPK values	Soroa (1953)	
	N emissions	Manure storage	IPCC (2006)	
		Manure applied	IPCC (2006)	
Fertilizers	Synthetic fertilizers	Applied	JCA(1921)	
		NPK values	Average values in: Aguirre-Andrés(1971) in Gallego (1986); García-Luzón (1922); López-Mateo (1922); Soroa (1953)	
	Organic non-manure	Deposition	Rodrigo(1998)	
		Free-Fixation	Loomis, Connor, & Cassman (2011) and García-Ruiz (2012)	
		Human excrements	Population settlements	Esteve-Palós (2003)
			Production	Gotaas (1956)
			Recollection	Garcia Faria(1889)
			NPK values	Annex 2.B
		Symbiothic N fixation	Legume crops	JCA (1923)
			Green manure area	JCA (1921) corrected, see text.
			Green manure NPK values	Average from Soroa (1953)
			Fix. Factors	García-Ruiz (2012)
		Seeds	Amount	Soroa (1953)
			NPK values	Soroa (1953)
		Irrigation	Irrigated area	JCA (1916; 1923)
			Water doses	JCA (1916)
			NPK values	(ACA 2000)
		Other	Applied	JCA (1921) corrected, see text.

			NPK values	Annex 2.B
	Manure	Manure	Livestock numbers	MF (1924)
			Live weights	JCA (1920)corrected
			Manure production	Average of values in Cascón (1918); JCA(1920)corrected , and references included in Marco et al. (forthcoming): Aguilera 1906; JCA 1892; Loomis, Connor, and Cassman 2011; Van Slyke 1932.
			NPK values	Annex 2.B
		Straw	Beddings	Cascón (1918)
			NPK values	Average from Annex A of the corresponding leguminous production of JCA (1923)

Chapter 6. Rabassaires, formiguers and *caganers*[1]:comparing two nutrient balances c.1860 and c.1920 in the northeast of the Iberian Peninsula[2]

1. Introduction

1.1. Aims and scope

The dominant socio-economic and socio-technical view on industrialisation as a gradual process of continuous growth and technological change can be complemented by focusing on changes in society-nature relations (Krausmann et al. 2008). Sieferle (2001)interrelated society-nature interactions with material and energy use historically. In doing so, hedescribed three socio-ecological regimes depending on the mode of appropriation of energy: uncontrolled solar energy use (hunter-gatherer societies), controlled solar energy use (agrarian societies) and fossil energy use (industrial societies). The periods of change between them are usually referred to as revolutions, although thinking of them in terms of Socio-Ecological Transitions provides more analysis potential (Krausmann et al. 2008; González de Molina 2010; Krausmann and Fischer-Kowalski 2013; Infante-Amate and González de Molina 2013). The transition to an industrial regime entails the progressive adoption of a new pattern of society-nature interaction along with its material and energy use, that could be understood as "a stepwise process of decoupling the supply of energy from land related biomass and from human labour on the land." (Krausmann et al. 2008).Indeed, the exploitation of finite stocks of fossil energy allowed societies to overcome the growth ceilings of agrarian societies,in turn creating new environmental problemsderived from the use of fossil energy and excess of synthetic fertilisers.

Our hypothesis is that, in the context of the late nineteenth-century Iberian Peninsula, a number of factors including the liberal reforms of the Spanish State, population growth, market integration (which in an extended area of Catalonia crystallised in vineyard specialisation) and urbanization,made the soil fertilitya critical issue. Moreover, replenishing soil nutrients was further hindered by the

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[1] Traditional Catalan figurine appearing in nativity scenes depicted as a peasant defecating.

[2]A versión of this chapter was galardonated with the IX award of the Sociedad Española de Historia Agraria (SEHA), and will be published in a forthcoming number of the Journal Historia Agraria. It can be found at: http://repositori.uji.es/xmlui/handle/10234/9274

social inequality that already existed in rural societies, which deepened from the end of the nineteenth century onwards. Nevertheless, if so, to what extent was the growing amount of nutrients extracted by crops replenished into the soil? The aim of this article is to search for historical answers to this general question by comparing the two agrarian systems of the last two chapters.

1.2. The Socio-Ecological Transition

The transition from controlled solar energy to fossil energy modes of appropriation occurred typically in two steps. First, a coal era coexisted with agricultural activities that remained organic; and second, an oil and electricity era pulled agriculture into the industrial mode. The first coal era[3]started in the United Kingdom around 1800, where 900 kg·cap^{-1} were used. A century later, the use of coal expanded to other places. However ,while most urban-industrial centres in other world regions had already begun the transition, over 70% of coal extracted globally was used by only four countries: UK, France, Germany and USA.(Krausmann and Fischer-Kowalski 2013).

Paradoxically, the use of coal did not replace the need for human physical work, but increased the demand for non-agricultural production. The same happened with the expansion of the railway and the need for draught animals as in combination they covered the increasing need for the transportation of goods and people. Hence, the number of draught livestock increased at the beginning of the twentieth century (Krausmann and Fischer-Kowalski 2013).. Consequently, the need for biomass (either as infrastructures, paper or food) increased (Iriarte-Goñi and Ayuda 2012), while the cultivable area and yields per areastagnated at the end of the nineteenth century in Western Europe. Most of the cultivated land relied mainly on organic fertilising methods, e.g. manure, green manure, deposition, etc., and the applications of guano, Chilean nitrates or superphosphates at that time were barely enough to supply all the required nutrients.

In the meantime,on the other side of the Atlantic ocean, USA's farms managed to export to Western Europe four million tonnes of cereal, enough to feed over 20 million people (Krausmann and Fischer-Kowalski 2013). Unlike European soils, the newly ploughed fertile soils of the American prairies produced, during the initial decades, high yields per hectare with low rural population densities,hence allowingfood exports to densely populated coastal urban centres or to Europe (Cronon 1991). This system functioned as long as it was possible to expand the

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[3] That of the subterranean forests of Sieferle (2001) or the *Coketowns* of McNeill (2001).

frontier and abandon lands with declining fertility. In some areas of the Great Plains the soils lost around 45% of their N content, and by 1870, as the frontier was closing, this led to fertility losses and subsequent declining yields in the first decades of the twentieth century (Cunfer 2004; Cunfer 2005).

Nevertheless, this situation changed in the second step of the transition. Since 1940, the use of cheap oil in the energy-consuming Haber-Bosch process allowed N fertilizer (Smil 2001) to be easily obtainable, the number of tractors started to increase, and the availability of electricity permitted the use ofgroundwater to expand the irrigated land (Cunfer 2004; Cunfer 2005). Besides closing the main nutrients gap through the industrial production of N, P and K[4], all these techniques and technologies allowed economies of scale in agriculture. These technologies were exported to Europe after the end of World War II, and then to the rest of the world. This mode of agriculture was intensive in energy use as it was developed when oil prices were cheap. This created a new relationship between industrial centres and the global periphery, introducing new ecological problems (Krausmann and Fischer-Kowalski 2013).

To complement this vision, González de Molina(2010) argued that, in Europe, the transition towards an industrial agriculture did not start after World War II but before, during the nineteenth century, and suggested that it occurred in a series of waves.

The first wave, entailed increasing the biomass production of the agroecosystems bythree means: increasing the extension of cropland for the provision of food, increasing yield per land unit (substituting human labour force by draught animals, eliminating fallow, introducing rotations, etc.), and specialising the production instead of maintaining a heterogeneous landscape[5]. The enforcement of one or more of these strategies depended on land availability, climate and soil conditions; hence, the role played by humans to maintain or increase fertility was a key point. When by 1870s American grains invaded the European markets (O'Rourke 2009), the strategy of importing the biomass that European agroecosystems were unable to produce prevailed over the other three (González de Molina 2010).

This had different effects in different European areas.In Britain, the most well-known case, the high farming (mainly the second of the above strategies) ended and animal breeding using American grains as feed expanded (González de

[4] Ca was restored through liming practices, which had been done in Europe previously.

[5]At the crop scale, this implied the loss of multifunctionality of some crops, as was the case of olive groves in Spain (Infante-Amate and González de Molina 2013).

Molina 2010; van der Ploeg 2014). In anycase, when humans were not able to replace the organic matter and nutrients, the increase in agrarian productivity was at the expense of the reserves in the soil.This led to an earlier European lossof soil fertility, as wouldlater happen in North America in the first decades of the twentieth century. To escape from this situation,it was necessary tofind external sources of fertility.Therefore, between the end of the nineteenth century and World War II, when coal was replaced by oil and natural gas and manual labour was replaced by machines, González de Molina(2010) suggested a second wave starting from the initiation of the use of synthetic fertilizers. Albeit not yet by the hand of the Haber-Bosch process for N. Although the weight of synthetic fertilizers was not as big as after World War II, its use along with guanos meant that the lack of nutrients started to be overcome by reducing the land cost of fertilization (González de Molina 2010), which was the main constraint in solar-energy based agriculture.

From the seminal works of Liebig and his discussions with the British agronomists Lawes and Gilbert during the nineteenth century, one can distil the following idea: it was not enough to apply a random quantity of manure in fields; to preserve or increase their fertility, it was necessary to refill the nutrients extracted by crops(Smil 2001). This idea was in the mind of the Spanish agronomists at the beginning of the twentieth century, who, in addition to pointing out insistently the low livestock densities and the ensuing chronic insufficiency of manure, recommended the use of other fertilizers (synthetic and organic) as an obligatory complement to manure (Llorente and Galán 1910; Cascón 1918; García-Luzón 1922; Rueda-y-Marín 1934). Along with the sellers of P fertilizers (Medem 1897), they argued that, although N was the main concern in agriculture,it was the main nutrient returned by organic fertilising methods, so there was a need to complement N with fertilisers rich in other nutrients.

Manure and other commercial fertilisers were expensive and as a result, some crops with lower relative nutrient needs such as olive groves or vineyards were not fertilised. Even, the belief that these crops did not need fertilisation was extended among farmers. Hence, some agronomists tried to refute this and provided other complementary sources of nutrients, cheap and available for farmers, such as human faeces, dry blood, shearing residues, or even the dead and dried bodies of locusts when there was a plague (López-Mateo 1922; Soroa 1929).

The elimination of fallows was also a matter of concern of the time and the use of rotations was highly recommended. Needless to say, the Norfolk rotation could not be reproduced everywhere, as clover, which played a more important role as a N fixing crop than other leguminous crops (Allen 2008), is more susceptible to aridity (the climate of Mediterranean Spain) than the more drought-resistant forage legumes, such as sainfoin(FAO 2012). Another purpose forleaving lands in fallow was to eliminate predators and competitors, i.e. weeds, and so enhance fertility. This is why other agronomists recommended the chemical disinfection of soils (Casado de la Fuente 1923) when fallows were eliminated. Although the reduction of fallowcould be seen as further evidence to an earlier starting point for the transition of the agrarian metabolism, for this study we left them aside, as well as other technical innovations not concerning the direct application of nutrients.

Beyond agronomists considerations, tenants and sharecroppers had to accomplish the contractual obligations of landowners concerning fertility, which started to be common in the second half of the nineteenth century.They could be, for example, the prohibition to sell the straw and the obligation to use it as bedding material for the manure of the farm, or the obligation to burn the pruning from vineyards in soil covered piles called «*hormigueros*» and use them as fertilizer (Saguer and Garrabou 1995b).

1.3. Nutrient flows, history and agricultural systems

Accounting for the flows of nutrients within a system allows analysing the impact of human activities in compartments of ecosystems throughout time.As an example,Kimura and Hatano, (2007) and Kimura et al., (2004) assessed the increasing N pollution in the agricultural system of the city of Hokkaido (Japan) due to the separation of consumption and production food sectors during the twentieth century;Lassaletta et al. (2013) analysed the increase of N emissions within Spanish river basins due to the change in diet pattern from 1960 to 1990; and Billen et al. (2007) explored the changing relationship between the population of Paris and the Seine river over 500 years through the quantification of N, P and Si flows. When applied to prior periods, the analysis of nutrients flows give information about the relation between fertility , mixed farming and convertible husbandry in England and Northern Europe until they reached productivity ceilings (Chorley 1981; Allen 2008).

The first wave of the Socio-Ecological Transition, however, happenedearlier in Mediterranean Europe due to water availability constraints, whose main effects were the lower livestock densities that could be maintained and the reduced capacity to grow leguminous crops (González de Molina 2002). The increase of monogastric animals (mostly mules) for transport and the trend to cultivate more cereal land pressured Mediterranean agroecosystemseven more, hence only the more productive land types were fertilized (González de Molina 2002). On the other side of the Atlantic, once the frontier was closed, the first wave gave way to the second in only in few decades (Cunfer 2004; Cunfer 2005).

In the South of the Mediterranean Iberian Peninsula it was argued that fertilising efforts were concentrated in some rotations such as *ruedo* and therefore mined the soils of others e.g. the extreme case of the olive groves (González de Molina 2002; González de Molina and Guzmán 2006). In the Northeast of the Mediterranean Iberian Peninsula, Tello et al. (2012) assessed the importance of cultural peasant practices when restoring nutrients in the municipality of Sentmenat circa 1860. By contrast, due to lack of data, they did not follow the nutrient flows in other (more arid) municipalities, crop type or rotation; but they conclude that to balance the soil nutrients some crop types like vineyards had to be short of nutrients. In the fifth chapter, we identified differences between Catalan regions in their capabilities to balance nutrients flows in cropland c.1920. The aim of this last paper is to compare the two balances c.1860 and c.1920. Some concerns about the scale and methodological differences are described in the following section.

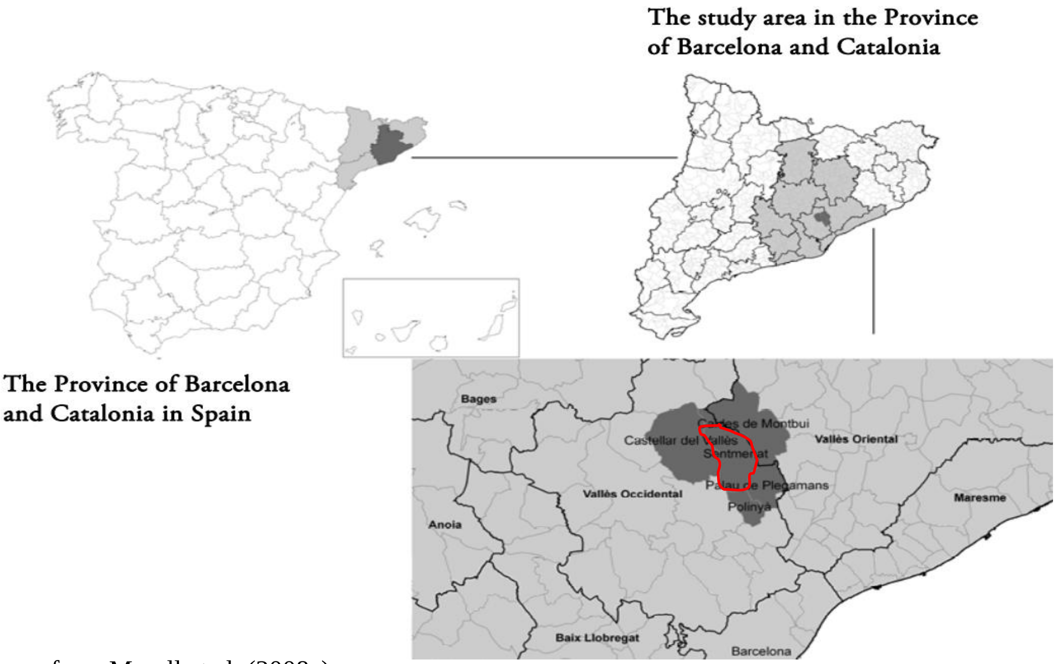
2. Material and methods

2.1. Sources and scale justification

As said above, the aim of this chapter is to compare two exercises of nutrient flow accountings within the framework of Socio-Ecological Transitions (Krausmann et al. 2008; González de Molina 2010; Krausmann and Fischer-Kowalski 2013). They represent a fixed picture of the first two waves of the Socio-Ecological Transition of agriculture in the North-East of the Iberian Peninsula. Circa 1860 represents the first wave, with the agro-ecosystem approaching its limits, whereas circa 1920 represents a system with one foot in the first wave and the other in the second.Before the comparison however, we should specify some differences concerning scale and method, which are the result of the historical processes that created the available sources.

During the nineteenth century, the configuration of the Spanish liberal State and a centralized tax office gave rise to the consolidation of a new and unified Spanish fiscal system. From then, a number of cadastral surveys and statistical information of the mid-nineteenth century are available as historical sources. Additionally, as areaction to the new taxes on land, some towns and villages all over the Spanish State declared land by providing detailed information about land properties, in the form of reports, maps, etc. However, contrary to the consolidation of other liberal states such as France or the Austro-Hungarian Empire, this process was done in a chaotic way and the information that remains today is far from centralized, complete and homogeneous. From 1860s onwards the main source for calculation of the State agricultural taxes were the «*amillaramientos*» surveys about rural properties and its monetary value, which is the main source that we use for theseyears (Muro et al. 1996).

Figure 6.1. Location of the study area: the municipality of Sentmenat and neighbouring townships in the province of Barcelona and Catalonia (Spain)



Source: from Marull et al. (2008a)

At first, these «*amillaramientos*» were conceived as a temporary expedient until the Spanish cadastre ended, but as this did not happen in the nineteenth century, they remained in a fossilized state.From the beginning of the twentieth century and until the end of themonarchal regime with the Second Spanish Republic, they became increasingly out of date. As a result, the tax system deteriorated and became increasingly conflictive, which also entailed the deterioration of the «*amillaramientos*» as a reliable historical source.

Hence, the «*amillaramientos*» have some disadvantages as a statistical source. First, as they were a fiscal instrument, some information could have been omitted or distorted to avoid the payment of higher taxes. Second, the information is rather general, they offer mainly total areas of irrigated and rainfed land classified by the main agricultural uses (grains, vines, olive orchards and other arboriculture crops, pastureland and woodland) without specifying rotations and fallow land. To turn this basic information on land uses into taxable incomes some converters such as, average yields, current prices of products and usual cost of the main inputs (labour, draught power, seeds, manure, etc.) were required. This informationwas provided by the «*cartillas evaluatorias*», a crucial document only rarely kept in local archives—thus obliging us to resort on the few that are available which do not always correspond to the particular local conditions of the area studied.Third, once the land of a municipal territory had been classified in the first «*amillaramiento*» only the final distribution of the tax burden according to the taxable incomes assigned were updated over time, this doesn´t provide enough periodicity to make a real series (GEHR 1991). Last, but not least, the information on land uses was only kept at municipal level and no aggregated statistics was compiled at district, provincial or national level throughout this period.

In 1879, *Ministerio de Fomento* established the *Servicio Agronómico de España* to centralize the surveys dealing with the agricultural sector. It was organized by the chief agronomist engineers of each province and a higher level of nine engineers located in the capital, which were known as the *Junta Consultiva Agronómica,* which published some reports until the reform of 1927, when a series of agricultural yearbooks started (GEHR 1991). Notwithstanding, the information that they generated in the first decades of its existence was incomplete and poorly detailed, and the local surveys that the engineers of each province used to compile in the provincial reports during all the lifespan of the*Junta Consultiva Agronómica* have never been found (GEHR 1991).

Summing up, for the years 1845-1865 we have a number of local sources, but it is almost impossible to find and group them to allow the aggregation at provincial scale or even other smaller administrative units such as the *comarcas* (similar to English counties). Then, from the 1860s to the 1890s there is an authentic statistical blackout, created not only by what has been explained above but due to the tumultuous period of the *Sexenio Revolucionario* (1868-73) and the Third *Carlista* War (1872-76), followed by a lack of interest in the first decades of the *Restauración Borbónica* (1974-1931) to renew the fiscal system. It was only after 1890, when the idea that the State had to become an active stakeholder in the economic improvement of the country, that we start to have a proliferation of aggregated statistical sources, by Province and sometimes by *Partido Judicial* (similar to English districts), but not local districts. As a result, from 1845 to 1865 we can carry out many local case studies but there are no historical series at provincial and national level. Ironically, after the statistical blackout from 1860 to 1890, we can start relying on the series and surveys compiled by the *Junta*

Consultiva Agronómica (JCA) at provincial or national level, but no local information is available.

As a local case study we selected Sentmenat, a municipality located in Vallès *comarca*in the province of Barcelona (Figure 6.1) c.1860 for the analysis. For two main reasons, the availability of sources and the long trajectory of research on these sources. The aristocrat lineage of the Marquises of Sentmenat had carefully preserved their patrimonial documents over the centuries, and they finally donated it to the main archive of Catalonia, the *Arxiu de la Corona d'Aragó*. The richness and detail of these records, allowed a number of studies.As the feudal and landlord bookkeeping together with copies of probate inventories and wills contained a great deal of information about land uses, crop yields, water conflicts, rents, tithes, wages, litigations, etc. (Serra 1988; Soto and Batet 1997; Garrabou et al. 2001b; Millán et al. 2006; Cussó et al. 2006b; Garrabou et al. 2010; Badia-Miró and Tello 2014).

Details of the nutrient balance c.1860 can be found in chapter 4 (Tello et al. 2012), and the sources are listed in table 4.7. On the other hand, for the analysis c.1920, we used the data at the only available scale, which was mostly at province level.Hence for crop production we used JCA (1923), for livestock numbers we used data from two livestock census (JCA, 1920; MF,1924), for the main fertilising materials we used JCA (1921) and we inferred irrigation doses using JCA (1916). The sources are listed in Annex 2.D. Criticisms and corrections of these specific sources were detailed in the last two chapters.

2.2. Methodological aspects

Both studies were made following the "Guidelines for Constructing Nitrogen, Phosphorus, and Potassium Balances in Historical Agricultural Systems" (González de Molina et al. 2010a; Garcia-Ruiz et al. 2012). Nevertheless, there are some differences in the methodology of calculating some of the nutrient flows between both cases.Especially regarding manure and humanure as a result of improvements on the methodology and correction of sources.

We augmented the number of sources of production and composition of manure and humanure. Two main concerns motivated this change: the huge potential variability of data—as production and composition of manure relies on a number of factors such as diet, age, activity— as well as the insufficient availability of dry weight data. Moreover, concerning humanure we adopted a new method to estimate the potential collection, taking into account the main disposal systems conditioned by the type of human settlements instead of only considering sewage systems as we did c.1860.

Hence we discriminated among scattered rural houses or groups of houses (populations that inhabit 10 buildings or less is accounted as *diseminados*or scattered by Nomenclator), concentrated rural villages and urban areas (Esteve-Palós 2003). While in our first analysis we omitted the variability, in the second analysis we decided to include the Standard Deviations to leave some space for variability and thus increasing the robustness of the analysis. The specification for these calculations, as well as the compilation from historical sources and the values considered, lengthen the list that appears in Lana-Berasain (2010), these are specified in Annex 2.B.

The next important difference concerned the emission of nutrients to the atmosphere or water bodies. We could not find historical sources for the losses of N, P and K although for the analysisc. 1860 they were presumably found in Cascón (1918).However, he only mentioned some experiments of N losses in manure in other countries and did not quantify nutrient losses on his farm, at least in the work cited, so we found an alternative way to quantify nutrient losses.

For the analysis c.1920 we used the "Guidelines of the Intergovernmental Panel on Climate Change"(IPCC 2006). They quantify the losses of N following two processes: through storage, which involved almost the 50% of the N in manure; and through land management, which involved other fertilizers, tillage and irrigation. The weak point of our estimation is that we needed to separate dung from straw (as the main losses occur in dung) and the production together with the composition data that we have is for manure i.e. dung and straw together. However, it can be done as long as we estimated the amount of straw used and its composition. These considerations apply to humanure as well.

In any case, we did not explicitly account for manure losses in the balance c.1860, although they were subtracted from the potential N inputs of manure. Simultaneously, we overestimated the losses from lixiviation, which in this case was close to the total of N losses of on balance. Considering a Mediterranean climate, to be compatible with the methodology we should multiply the lixiviation factor only by irrigated land and not by all the cropland area, and hence the value would drop from 5.5 to 0.23 kg of $N \cdot ha^{-1}$(Figure 6.3). Yet, the overall result for N would not have changed that much as it would be compensated by the increase of N denitrification of managed land, which according to the IPCC (2006) methodology would have rose from 1.5 to 6.5 kg of $N \cdot ha^{-1}$ approximately. Something similar would have happened with K losses, however as given they would be negligible (Garcia-Ruiz et al. 2012), the amount considered c.1860 is so low that they could have been compensated by other minor differences without affecting the overall balance significantly.

We reviewed a number of historical sources written by Spanish agronomists at the end of the nineteenth century and the beginning of the twentieth for the analysis c.1920. Among the recommended manure applications, we only found the already mentioned amount of 6-7.2 $t{\cdot}ha^{-1}$of fresh manure (Llorente and Galán 1910), but we could not confirm the 10 $t{\cdot}ha^{-1}$wrongly attributed to Cascón (1918) in the analysis c.1860, as he only stated that he used 20 $t{\cdot}ha^{-1}$ to fertilize his own farm (Cascón 1918). In any case, all the agronomists of the time were concerned about the low availability of nutrients, and their advice was not limited to a fixed amount of manure as they recommended quantifying the extractions of nutrients in order to return them to the soil using all possible combinations.

3. Discussion

3.1. Socioeconomic features

Low livestock densities, low share of forest and pasturelands, and vineyard specialisation of Sentmenat c.1860 were argued to be typical of a Mediterranean-type of «intensive organic agriculture» (Tello et al. 2012). Vineyard specialisation played a key role by complementing forest produce, such as prunings burnt as fuel or as fertilizer in *hormigueros*, leaves, shoots and pomaces as animal feed or fertilizer (Cussó et al. 2006b), as was done for centuries in the great diversity of silvoarable landscapes of Europe (Eichhorn et al. 2006). Indeed, the low forest, scrubland and pastures ratio per unit of cropland was a matter of concern at the end of the nineteenth and the beginning of the twentieth centuries. As claimed by Huguet del Villar in 1921, when he stated that, in Spain, forest land was only between 10 and 15% of total area (Tello and Sudrià 2011). This number is similar to that found in the plains of the province of Lleida in chapter five and was probably shared with other cereal regions of the Castilian plains, but is lower compared to our case study (Table 6.1). The general trend in comparing Sentmenat and the province of Barcelona was an increase in the share of forest, scrubland and pastures[6].At the same time, the complementary function of the vineyards lost importance, as the multifunctionality of arboricultural crops lost

[6]We could not disaggregate between forest, scrubland or pastures as in JCA (1923) forest and scrubland are considered adjoined to pastures.

importance in other places of the Iberian Peninsula (Infante-Amate and González de Molina 2013; Cervera et al. 2014).

Other indicators are difficult to compare as the province of Barcelona was strongly influenced by Barcelona city. However the census of population (INE, 1920) and livestock (JCA, 1920) allowed to separate the *Partido Judicial* of Barcelona from the rest of the province, showing that while the population density in the later increased up to 84 inhab·km^{-2}, the increase in livestock density per cropland area was not so dramatic (14 LU 500 kg·km^{-2}). The high concentration of people and manure involved high concentration of organic matter, therefore, the cropland areas surrounding the city of Barcelona took advantage of this flowfrom the city, as with other cities such as Paris (Barles 2007; Billen et al. 2007b). Notwithstanding, lacking other data sources, we could not refine this supposition.

The range of population densities between 16-64 inhab·km^{-2} was considered by Boserup (1981) typical of agricultural systems that combined short rainfed fallow with domestic animals. At the same time, Badia-Miró et al. (2010) found that the optimal population density in vineyard areas in Cataloniaduring the 1860s-1880s would have been between 25 and 40 inhab·km^{-2}. In contrast with the low population densities of Lleida province, which match those of Castilian grain areas. Barcelona province c.1920overcome that threshold, regardless of taking into account the city of Barcelona or not, thus indicating that the agri-food system had started to change profoundly. Gini index[7]c.1860—not available for c.1920—showed lower levels of inequality in land distribution compared with the previous local situation in the eighteenth centuryor with the latter in the first third of the twentieth century.These lower levels of inequality were linked to access to land. Which were due to the spread of *rabassa morta* sharecropper leases,these were strongly linked with the vineyard specialisation in Catalonia before the twentieth century (Badia-Miró and Tello 2014).

[7] The Gini index measures the inequality among values of a distribution. The lower the index the lower the inequality. In this case, Badia-Miró and Tello (2014) apply the Gini index to land distribution.

Table 6.1. Main characteristics of the case studies

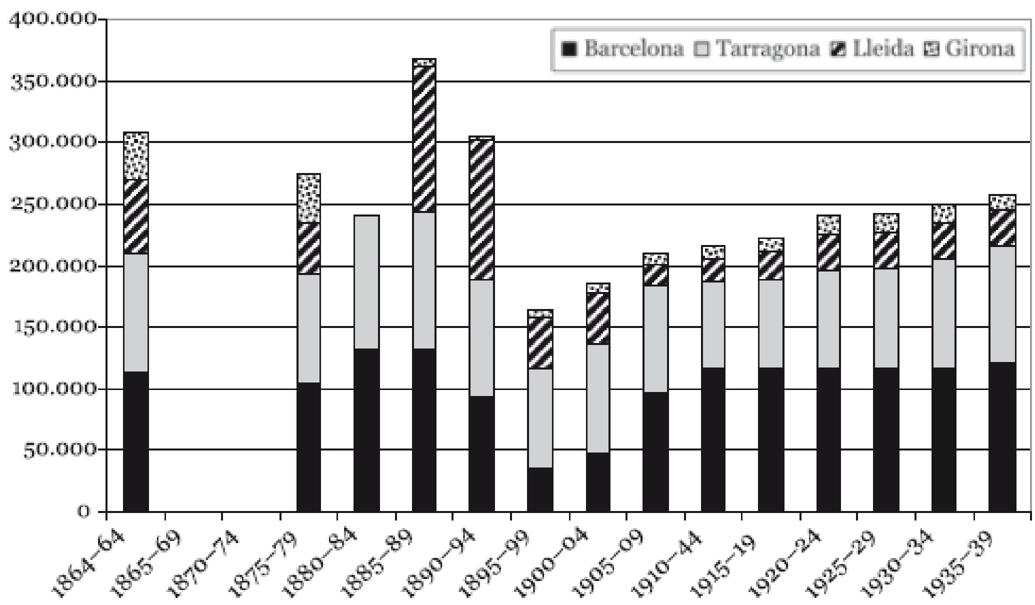
	c.1860 Sentmenat	c.1920 Barcelona
Rainfall (mm)	643	640
Population density (inhab·km^{-2})	59	176
% forest, scrubland and pastures over total area	37.8	56.9
Ratio forest, scrubland and pastures over annual crops[8]	2.4	3.5
Ratio permanent land covers over annual crops	5.1	4.9
Livestock density per cropland area (LU 500 kg·km^{-2})	12	40

Source: last two chapters.

Vineyards had occupied and occupy important cropland extensions in Catalonia and their changes between c.1860 and c.1920 (Figure 6.2) had important effects at all levels: "Catalan vineyard specialisation cannot be seen as a simple market-driven resource reallocation, undertaken only according to a given set of agro-climatic features. The active development of second-nature factors was very important, thus confirming the role played by socio-institutional settings and socio-political conflicts related with income inequality. While in the mid-nineteenth century vineyard spread had led to a less unequal rural society, it was also growing faster there than anywhere*else*. This explains why the *rabassa morta* sharecroppers fought so fiercely during the second half of nineteenth century and up to the Spanish Civil War (1936–39)."(Badia-Miró and Tello 2014).

[8]Although questionable, we refer to *herbaceous crops* and *annual crops* indistinctly when we want to group all the crops that are not wooden and perennial.

Figure 6.2. Vineyard land in the four provinces of Catalonia, 1860-1935



Note: The y-axis is in ha and 1880-84 data are only available for the provinces of Barcelona and Tarragona. Source: from Badia-Miró et al. (2010, 42).

Before becoming a cash crop, grape vines used to be planted as a temporary crop, slashing and burning forest or scrublands(Miret 2004), it was common to leave land between rows of vines to be sown alternatively with grains or left to fallow (Badia-Miró and Tello 2014). Unlike other winegrower areas of the Iberian Peninsula specialized in luxury wines such as Porto, Malaga or Sherry, the Catalan vines produced cheap table wines.Exportation, oriented to an elastic demand, started to grow at the end of the seventeenth century.

The majority of the expansion of the vineyard area was at the expense of woodland or scrubland, and under the sharecropping contract called *rabassa morta*, which ended when two-thirds of the vines had died. Since the consolidation of the Spanish Liberal State the aristocratic landlords lost the right to ask for tithes and some of the wealthiest sharecroppers got access to land. Both found in the *rabassa morta* a way to receive rents and expand cultivated land without assuming the labour costs (Valls-Junyent 1997; Colomé 2014). The end of these contracts was undefined and it could be sold or even inherited due to layering practices,which extended the lifespan of the plantation, not without controversy (Congost 2004). This system allowed landless peasants to have a kind of long-term access to land up to the second half of the nineteenth century,hence creating the effect of land distribution, as forests used to belong to big landowners.Besides wine, vines were an extra source of fuel (pruning) and feed for livestock (vine shoots, leaves and grape pomaces) (Garrabou et al. 2010) akin to forests. Wine prices were highly fluctuating andthese indefinite contracts based on a fixed rent started to create problems when inputs required (such as pesticides) increased(Carmona and Simpson 2009). This happened during the nineteenth century, when the demand of wines peaked due to the spread of two plagues unknown to European winegrowers but common on the other side of the Atlantic.

The *oïdi, oidium* or powdery mildew (*Uncinula necator/ Oidium tuckeri*) was detected for the first time in 1845 in the United Kingdom and spread through France between 1852 and 1861. Thisproduced a dramatic decrease in French wine production, which could not supply the American and English markets, nor the French itself (Piqueras-Haba 2010). While the plague spread across the Iberian Peninsula as well, its virulence was lower in those areas with arid and drier climates like the inner *comarques* of Bages, Conca de Barberà, Garrigues and Priorat., There new land was ploughed, taking advantage of the international situation of prices, thus increasing massively vineyard acreage. On the contrary, on the coastal and humid areas of the provinces of Barcelona and north of Girona,the effects of the plague were exacerbated and together with the abridgment of fungicide availability (sulphur in this case) and other factors, some winegrowers decided to uproot their vines. The recovery of the vineyards from these areas started in 1858 (Piqueras-Haba 2010) and so did the relative prices of wine/wheat.Which rose again at the end of the 1870s until the beginning of the 1890s due to the spread of the *phylloxera*(Carmona and Simpson 2009).

During the late 1850s,*fil·loxera, filoxera* or phylloxera (*Dactylosphaera vitifolia or Phylloxera vastatrix*) was introduced accidentally in Europe through the imports of American varieties of vines resistant to powdery mildew, and by mid-1890s, there was not a corner in France free from the insect (Piqueras-Haba 2005). In order to supply the French internal demand, not only did imports from their Mediterranean neighbours increase, but also vineyards started to be plantedin Algeria. The phylloxera has a complex reproduction cycle and attacks the root system of the European varieties until death, whereas the root system of the American varieties resists. The only solution was (and still is) to graft the European varieties with American rootstocks or use hybrids resulting from crossing varieties from the two continents. The spread of the phylloxera across the Iberian Peninsula had two main outbreaks, in Porto (1871) and Malaga (1878).However, the expected arrival from France was detected for the first time in Girona (1879) and took more than 25 years for it to reach the last vineyards in Tarragona and Lleida (Piqueras-Haba 2005). Hence, Catalan winegrowers could still take advantage of the favourable prices, either by replanting the first destroyed vines or by planting new ones in the last affected areas. Such was the case of Lleida, where during this period the area of vineyards almost doubled. As they were using pre-phylloxeric varieties however, at the end all of them were destroyed.

The formerwas the case for Barcelona and Tarragona, where the vineyard area increased only 15% during the phylloxera's bubble and the winegrowers were able to replant the dead vines with other ones resistant to plague, so they recovered the vineyard area of the previous years, according to Badia-Miró et al. (2010). These authors argue that a key component for the recovery of these two provinces was that of path dependence. In other words, as they started their vineyard specialisationin the seventeenth century, the culture and social fabric co-evolved with vines, thus creating a sort of comparative advantage when the vines were exterminated and it was time to leave agriculture, move to another crop or replant vines.

After the phylloxera plague, viticulture became something totally different. Many investments had to be done for replanting the dead vines: buying them from nurseries and grafting them (and learning to do it); protecting them from the diseases that accompanied the American rootstocks such as the *mildiu* or downey mildew (*Plasmopara viticola*) and to fertilize them (recall that the pre-phylloxera vines were not fertilized). As a result this new viticulture needed more labour than before, up to 94 man-equivalent working days per year per hectare, vis-à-vis the 25 needed in extensive cultivation of cereals with fallow that was practiced in inland Spain and the province of Lleida, were population densities matched those in Castile during 1860–1920 (Badia-Miró et al. 2010). Moreover between 1890 and 1930 wine prices decreased and winegrowers had to face several *crises de mévente*, when prices of wine were lower than production costs, something unknown for Catalan winegrowers since 1850 (Planas 2014). The decrease of wine prices in respect to bread prices, and particularly with respect to wage labour, created an opportunity cost for sharecroppers with respect to off-vineyard land and off-farm activities (Carmona and Simpson 2009). Needless to say, with all the vines wiped out and the impossibility of layering or transplanting cuttings, all the *rabassa morta* contracts ended.

Under these conditions, in the succeeding years of the phylloxera, a bulk of rural population migrated towards urban and industrial poles, hence boosting the growth of large cities like Barcelona, as was happening in other European countries during this *fin-de-siècle* agrarian crisis (Colomé and Valls 2012). Some rural areas began a process of demographic transition towards the current pattern of low birth rates (Colomé and Valls 2012). This was not the end of the existence of the *rabassa morta* contracts, whichstill were the contracts dominating the relationship between sharecroppers and landowners at the beginning of the twentieth century, although they were modified. Indeed, the undefined lasting terms of the contract were changed during the nineteenth century, as the landowners wanted to facilitate the eviction conditions. For example in the Penedès *comarca*, one of the most specialised vineyard areas in the province of Barcelona, more than half of the contracts already specified a fixed duration in the decade of 1850s and 100% after the phylloxera plague (Colomé 2014). However Carmona and Simpson (1999) argued that although the contracts changed its name and conditions, the path dependence and social pressure in the areas where vines were replanted were so strong that in practice everything remained the same. So, while for some authors this was the starting point of the constrictionof the conditions imposed by landowners (because sharecroppers were losing the property of the vines); for others it is the demonstration of the high transaction costs for both sides to change to another alternative such as renting.

Going in depth into this debate, Badia-Miró and Tello (2014) tried to explain the apparent contradiction in the expansion of vineyard land (and so *rabassa morta* contracts) before the decade of 1850, when the relative prices of wine were fluctuating vastly(Badia-Miró and Tello 2014). These authors explain that the vineyard specialisation in Catalonia enhanced the capacity of rural areas to sustain population. As this expansion was done through the use of *rabassa morta* contracts, which previous to the phylloxera attack allowed access to land for small growers with little or no land of their own hence, retaining them from migrating to urban environments or the New World. This, as expressed by the lower rental-wage ratios of this period, resulted in lower inequality levels for those municipalities whose major cropland area were vineyards compared to municipalities devoted to grain.

This trend ended circa 1840, when vineyard areas reached a critical threshold in population densities and the rental-wage ratios increased in winegrowing areas and decreased in grain areas. Thus, from circa 1840, inequality between landowners, tenants and sharecroppers started to rise again whereas it diminished in grain-growing areas. This explains the social unrest be found in winegrowing areas at the end of the nineteenth century and the beginning of the twentieth century (Badia-Miró and Tello 2014).

Responses to face the conditions after the phylloxera plague were not only centred in rents and land contracts. The new situation fostered the creation of wine cooperatives in Catalonia, which unlike the French ones, were platforms to buy inputs for agriculture, find credit and have access to affordable wine processing facilities. However, by no means the main objective was improving the quality of wine(Planas 2013).In addition, the conflict between big landowners and small winegrowers was transferred to this institutional ambit, and it was possible to find two cooperatives grouping members of each side fighting in the same village(Hansen 1969; Simpson 2003; Planas 2013). Again, contrasting the French case, the Spanish cooperatives suffered a lack of support from the state(Planas 2013).

Still, the local government of Catalonia helped in the creation of cooperatives: in 1919, the *Mancomunitat* launched a service to encourage the formation of new wine cooperatives and assist them (*Servei d'Acció Social Agrària*). These services were closed down after the Primo de Rivera coup d'état (1923) and reopened again during the Second Republic by the *Generalitat* in 1931 (Garrabou 2006). In 1934 only 16% of all the wine produced in Catalonia came from cooperatives, so although it was by far the region of Spain with more cooperatives (3/4 of the over 100 Spanish wine cooperatives were from Catalonia), the success of its spread was modest (Planas 2013).

Winegrowers, being aware of the French opposition to Spanish wines, tried to pressure for favour of regulation of the domestic market to use the distillates sector as a destination for the overproduction of wine. Nevertheless, they had strong internal conflicts and were not such a strong lobby as the producers of "artificial" wines and the alcohol industry (alcohol from sugar or starch was used to strengthen wines to export them during the plague) (Planas 2014). At the same time, the main demand from sharecroppers was towards land ownership recognition, while landowners were more worried about wine taxes. In fact, the main landowners associations, the *Institut Agrícola Català de Sant Isidre (IACSI)* and the *Federació Agrícola Catalano-Balear*, were even more concentrated in the technical aspects of vine cultivation than in establishing measures to control fraud or wine quality.Contrary to what happened in the French Midi with the *Confederation Générale des Vignerons*, which allowed improvement of the quality of wines and so the price (Carmona and Simpson 2009; Planas 2014). Nevertheless, the weakness of the winegrower groups was not the only factor that contributed to the failure of the creation of an institutional framework favourable to the Spanish winegrowing sector. Also, their lack or bad relationship with political parties and the State's inability to respond to their demands, as opposed as to what happened in the French Midi (Planas 2014).

3.2. The Socio-Ecological Transition c.1860 - c.1920

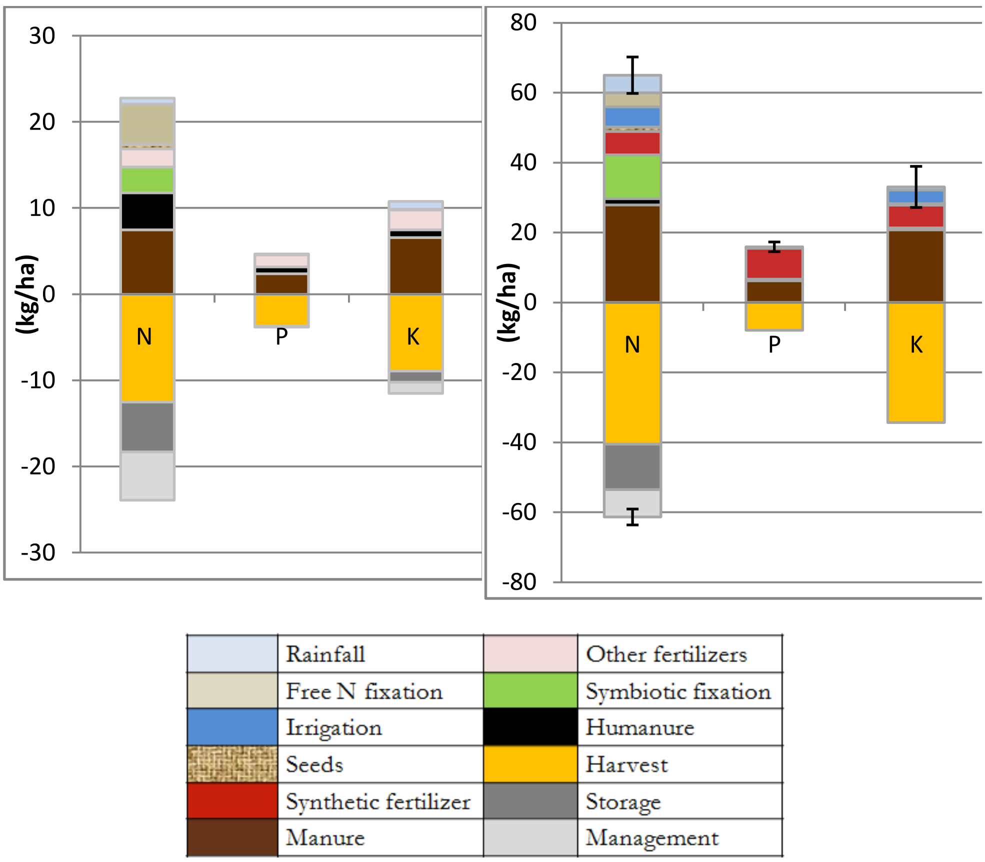
The weakest point of the balance in Sentmenat was N, while K and P were almost in equilibrium; conversely, the most unbalanced nutrient c.1920 was K, whereas the extraction of the other two nutrients analysed were compensated by the inputs (Figure 6.3). Note that the main difference between the two balances in this figure is the *scale* of the flows, i.e. the magnitude of both positive and negative vertical bars. Two main reasons explain this difference: the spatial scale and the Socio-Ecological Transition.

Regarding the spatial scale, despite more than half of the cropland area being vineyards in both cases (66% and 55% c.1860 and c.1920 respectively), the province of Barcelona was not as homogeneous as the municipality of Sentmenat. Some geographic factors,the mountains, sea, etc., or the existence of urban centresas the city of Barcelona and its port, would have structured local possibilities and demands for some crops. To serve as an example, adjacent areas to the city would have benefited from the marketed humanure (JCA, 1921) and manure dumped by the high livestock densities c.1920, but not more distant areas.In addition, the cereals yields in the Vallès area could have been lower than in other places of the province of Barcelona such as Osona (Garrabou et al. 1995). These effects however cannot be discriminated in the provincial balance, as we cannot decrease the scale of yields.

As for the latter, to what extent the different moments of the Socio-Ecological Transition explain lower fertilizer flows and lower yields? Although the balance of Sentmenat c.1860 is not in equilibrium, the negative trend is not as strong as the one found in the more arid regions of Catalonia c.1920. Thus, we could say that, from this point of view, the system was not so close to its limits mainly because the extractionskept up with the availability of fertilizers. Considering that a global abundance of fertilizer would mask local scarcity of fertilizer, there was more manure available c.1920 than c.1860 (4.57±0.68 vis-à-vis 1.4 $t \cdot ha^{-1}$ respectively). Theoretically, two main reasonscould explain the lower extractions c.1860: lower intensity in the use of nutrients and lower yields. Unfortunately, we cannot specify nutrient variations in the composition of ancient crop types and cultivars due to lack of reliable information (we had to use the same sources in both years for nutrient content). Concerning yields,although presumably these were lower c.1860, we considered that it was not worth comparing quantitatively two moments of time because the annual variability could lead us towards uncertain conclusions—*cartillas evaluatorias* used to be five-year compilations and the report from *Junta Consultiva Agronómica* only related to one year.

Still, as in both cases more than half of cropland area were vineyards, we can make an important observation.Recall that they were not the same type of vines due to the phylloxera plague at the end of nineteenth century. On one hand, the extractions were of a different kind, as pre-phylloxeric vines produced much less fruit (Marco et al., forthcoming.). On the other hand, vineyards allowed cultivating poor land without great fertilising efforts, due to the lower relative needs of N and P compared to other crops. Hence, this first wave strategy to increase marketable agrarian produce—but also access to land and availability of forest-like produce—concentrated high levels of soil mining c.1860, as vines were not fertilized at all.

Figure 6.3. Nutrient balance of the cropland area of Sentmenat c.1860 and the province of Barcelona c.1920



The nutrient balance of the cropland area of Sentmenat c.1860 has been adapted to the legend of c.1920 in the Barcelona province, but note that they are not at the same scale. Negative values represent extractions and losses, positive values are additions of nutrients. Error bars are the accumulation of Standard Deviations and are due to the estimation of manure, humanure and the N emissions associated. Source: Tello et al. (2012) and our own as described in text.

The origin of fertilizers strongly differed in both cases. The non-manure organic fertilizers had more weight c.1860 than c.1920 in the replenishment of all nutrients. Among them, free fixation is the main source of N c.1860,while c.1920 has nearly the same amount, it has not the same relative importance. Rainfall deposition of N is not the same due to calculation differences. N fixed by leguminous crops is higher c.1920 because a greater area of cropland was devoted to them. The use of humanure is higher c.1860 despite lower population densities as less was lost due to the disposal system type, opposite of what happened in the city of Barcelona, where the proximity of the sea and bad conditions of the sewage systems (García-Faria 1893)allowed less recovering of humanure. The rest of fertilizers that we grouped as «other» (*homigueros*, ashes and other materials buried) were higher c.1860 than c.1920. The reason is that we could not quantify them c.1920 as in contrast to neighbouring provinces, they were neglected by the agronomist in charge of Barcelona (JCA 1921). These other fertilizers could respond to practices relevant at local level but were diluted at a more aggregated scale.This could explainwhy the engineers of the*Junta Consultiva Agronómica*did not consider them—although it is rather likely that the significant rise in agricultural wages experienced between the two dates (Garrabou and Tello 2002), together with the peak of deforestation attained during the First World War (Cervera et al. 2014), would have reduced these fertilising practices (*hormigueros*). Two new fertilizer applications appear c.1920: one due to nutrients carried by irrigation water, applied mainly in horticultural land, and the other due to synthetic fertilizers.

The flows of nutrients out from cropland area in the province of Barcelona could be balanced due to the incorporation of synthetic fertilizers to the mix of fertilising methods (Figure 6.3). Nevertheless, were there other alternatives to increase nutrient flows towards croplands? In past organic agricultures, there were mainly three ways to do it. First, increasing the recycling of nutrients: seeds contain nutrients that the plant needs to grow, so the lower the yield of the seed the higher the nutrients recycled (Chorley 1981); the use of by-products from crops as fertilizer being buried, as a component of manure heaps or as feed for the animals, and the use of humanure. Second, transferring nutrients from nearby uncultivated lands as biomass to be buried and as feed for livestock—yet, to what extent could biomass be extracted from Mediterranean forest or scrubland (whenever it was allowed by the owner) without damaging the capability of providing ecosystem services or its regenerative structures? Third, the availability of stocks from the atmosphere and soils could be increased (through atmospheric N fixation or mineralization from soil). Leguminous crops in Sentmenat c.1860 were 9.6% of cropland but 35.7% of annual crops, whereas in Barcelona province c.1920 they represented 10.8% of total cropland area and 25.1% of annual crops. Could it have been possible to increase even further the area of leguminous crops? Also, not all leguminous crops behave in the same way: wheat yields more if planted after clover than after beans (Allen 2008). Was it possible to increasefurther the area sownwith clover or other leguminous forages more drought resistant as sainfoin?I deem that, from all the fertilising methods described so far for the system c.1860, the only way to increase the nutrient flows escaping from the zero sum game of land dependence was the reduction of nutrients losses throughout the fertilising processes.

Then there were all the socio-economic factors, e.g. human labour, market profitability, inequality. The well-known case of the English high farming system prior to the 1870s becomes a useful reference. In spite of the contemporary observations of Liebig and Marx (Foster 2004), other authors recently argue that it was more ecologically sustainable than it could have seemed,as with convertible husbandry and rotations with leguminous plants, they were increasing production by enhancing internal ecological processes. What was unsustainable were inequality and exploitative social conditions by landowners and capitalist tenants (Schneider and McMichael 2010). "Yet High Farming succumbed not to social inequality or popular resistance (the Luddist uprising) but to exposure to world commerce"(Friedmann 2000)—that is, by the 'grain invasion' (O’Rourke 2009) from the American Great Plains which still did not have fertility concerns.

4. Final remarks

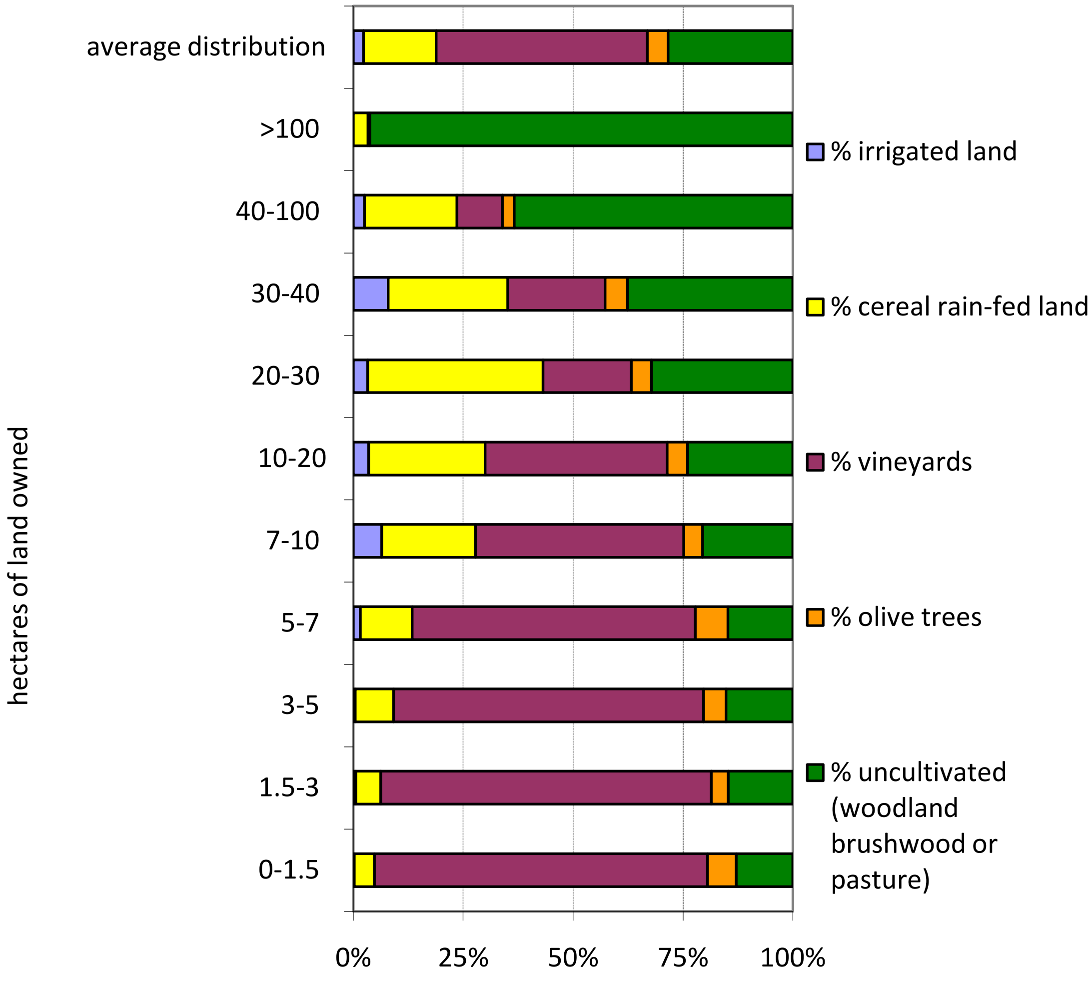
Recalling our main hypothesis, the repositioning of nutrients—that was strongly related with other physical factors such as water availability as we saw in last chapter—was a weak point of the past organic agricultures stressed by market forces, increasing inequality, urbanization and a growing population. Hence, we end with a big open question: which were the social and economic factors affecting soil fertility? I guess answering this question requires a complex combination of geographic, demographic, socioeconomic or political and cultural factors. Examples of these could be population densities and livestock densities, settlement patterns, social inequality in land ownership and income distribution, the advance of a market-oriented agricultural specialisation of a former crop diversification with multiplicity of land uses, or the ways of transmitting a peasant traditional knowledge versus the new technologies provided by scientifically based agronomics. Further research is needed before trying to construct such an ambitious historical synthesis that would require combining different approaches taken from cultural, political, socioeconomic and demographic history, as well as from environmental history. This becomes an unattainable aim for this historical study based on the Material Flow Analysis methods applied from an environmental history viewpoint, which is more focused on contributing to the pending historical narrative of Socio-Ecological Transitions in Mediterranean agriculture.

The comparison with the adjacent regions was interesting due to the strong differences among them. In the province of Girona medium-sized farms (*masies*) with a rather complex and equilibrated policultural endowment of arable land, woodland, pastures and livestock were common. In addition to being located in the more rainy area of Catalonia, this agrarian class structure was arranged in a habitat of scattered farms, which mainly explains how they could still enjoy enough manure to replenish the soil nutrients without having to resort to chemical fertilizers c.1920 (Pujol 1998). This was also probably true in the mainly forestry and livestock breeding rural communities located along the Pyrenees. Both were unequal rural societies, where a stratum of peasant families lacking enough land of their own had to work for the wealthier owners as sharecroppers, farmhands or daily workers (Congost 1989; Congost and To 1999). These regions, however, neither generated a great surplus of landless people lacking a contractual link with the well-established families, nor forced them to emigrate to other Catalan places (like the ones who migrated over centuries from the mountains towards the lowlands in the provinces of Barcelona and Tarragona).

Conversely, the littoral and pre-littoral fringes of the Barcelona and Tarragona provinces experienced an increase of population densities because of the growing number of landless people seeking an opportunity to make a living. For a while, the owners of the land saw them as a trickle of foreign tramps who could become potential thieves of their own wellbeing. They were becoming a new frightening class of people without a place in traditional Catalan rural society (Tello et al. 2008a; Garrabou et al. 2010). A response to this challenge was the opening of the vine-planting frontier (Badia-Miró and Tello, 2014) in former scrubs and woodland areas that we described above which together with the spread of industrious activities and the increase in industrial activities near the network of cities and towns with close access to seaports (Espuche 1998; Marfany 2012). The advance of this vineyard frontier turned viticulture into a cash crop exported to the emerging Atlantic economy, and entailed a cropland expansion as well as a land-use intensification that put additional pressure on the replenishment of nutrients extracted from soil.

We have seen that c.1920, the increasingly polarized and evolving agrarian world in Barcelonaprovince could no longer equilibrate their nutrient balances without resorting to chemical fertilizers. We deem that before the arrival of these industrial fertilizers a soil mining process had been in place, mainly in vineyards and perhaps other perennial crops like olive, almond and nut orchards. A pending issue that needs further research is to what extent this imbalance existed simply because there were too many people demanding too many crops being grown on the land, or rather most of this soil mining process had been driven by social inequality in a rural society increasingly polarized. From the data collected c.1860 in Sentmenat, it was concluded that vineyards were under-fertilized not because there were insufficient organic fertilizers but mainly due to the lack of access of many small winegrowers to livestock, pastureland and woodland (Tello et al. 2012), as it can be understood by considering land distribution (Figure 6.4).It is likely that inequality also played a role in the lack of manure as well as chemical fertilizers to fill de nutrients gap we found in the arid inland planes of the Lleida province.A rural world highly polarized between irrigated and rainfed poor lands and where a myriad of small peasant families had to fought hard to succeed under a dense web of debts owed to a minority of wealthy landowners who grabbed the best land and water resources (Vicedo 1991; Tello 1995).

Figure 6.4. Allocation of land according to the range of land owned in Sentmenat (Vallès *comarca*, Catalonia, c.1860)



Source: from Garrabou et al.(2010).

Therefore, I have to conclude by raising a big question that deserves to be addressed in the future by joining Environmental History and Socio-economic History standpoints: would it have been possible to increase the capacity of agriculture to produce more in a sustainable way or was the only possible way industrial agriculture?

Final remarks

In this work, we examined the Socio-Ecological Transition of agriculture in the Northeast of the Iberian Peninsula. As we quoted at the beginning of this dissertation, this framework embeds the old question about agriculture that other Prometean views of History abandoned after the spread of industrial agriculture (Barca 2011). Industrial agriculture is not only vulnerable to the depletion of finite stocks of fossil fuels, but it has also harmful effects on soil fertility, biodiversity and local knowledge, regardless of the agroecosystem it relies on.

We adopted as our framework the narrative of Socio-Ecological Transitions (Krausmann et al. 2008; González de Molina 2010) to integrate the bio-physical analysis in Agricultural History. It has been useful to integrate the society–nature interaction within the field of Environmental History to study the transition from one agrarian society to an industrial society. This is so because the knottiest issue of comparing systems during the transition is that they do not rely on the same sources, logics and systems of value. Relying only on a modern function of production factors involves the misunderstanding of logics that were dominant in past systems (Naredo 2004b). For instance, the strategies relying on decreasing labour productivity (Boserup 1965) or the paradoxical observation that petty commodity producers were behaving in a more capitalistic fashion than big landowners hiring wage labour (Garrabou et al. 2001b). The Socio-Ecological Transition narrative (Krausmann et al. 2008) and the proposal of its arrival through twofirst waves depending on the management of fertility(González de Molina 2010) combines two interesting logics: the capabilities of agrarian systems to improve yields but also to keep doing it in the long run. Our aim here is to interpret and reflectour results under the umbrella of the Socio-Ecological Transition.

Although the entire agricultural sector wasin crisis during the late nineteenth century, it ensued in contrasting paths across the Spanish regions. We chose Catalonia because of the paradigmatic differences in its rich historiography, between winegrowing and cereal areas and also between interior and coastal areas. During the nineteenth century and the early twentieth, the winegrowing areas in Catalonia followed a particular path. First by the expansion through the *rabassa morta* sharecropping contract and later contracted because of the phylloxera crisis, whose way out was strongly marked by social conflicts. The interior dry-farming areas such as the plains of Lleida, struggled with low and fluctuating cereal yields during the nineteenth century, whereas during the twentieth century the cereal mix focused towards wheat, and yields stabilised (Garrabou et al. 1992a;

Garrabou et al. 1992b; Garrabou et al. 1995). In the non-interior cereal areas, yields used to be higher because other settlement and climatic conditions allowed higher livestock densities (Garrabou et al. 1995).

1. Bloc 1. Energy flows of five villages in the Vallès county (Barcelona) c.1860 and 1999

In the first bloc, we analysed the energy flows of five villages in the Vallès county c.1860 and 1999. Their comparison showed the paradigmatic trend that followed the agricultural systems once they ended the Socio-Ecological Transition of an industrial regime or mode of appropriation. Starting from the concept of Energy Return On Investment (EROI)(Hall et al. 1986) we defined three ratios— Final EROI, Internal Final EROI and External Final EROI—to capture three aspects of the energy profile.

The energy efficiency, either considering onlyexternal inputs or total inputs consumed, decreased. Opposed to this, the efficiency of the use of crop residues increased as the harvest increased together with the diminution of the harvested biomass reinvested in the system—due to e.g. lower straw/grain ratio, less cropland area devoted to feed, etc. Hypothetically, the margin to improve the overall efficiency c.1860 would be to decrease losses of nutrients as qualitative observations of the agronomists at that time suggest.

In addition, we defined the NPP EROI as the return of energy available to sustain humans as well as the rest of heterotrophic species. To understand the idea behind the fourth ratio, it is essential to understand the concept of agroecosystem as hybrid human-natural systems in whose arena interacts the correspondent ruling and driving forces. We deem that just as some human activities harm biodiversity, others can stimulate it. Hence, although agriculture is always a disturbance, depending on its characteristics, it can have a synergic relation with biodiversity as some agroecologists have observed. As we largely developed in chapter 3, at landscape scale this means to recover the old idea of a mosaic of land uses (Margalef 1968). To adapt this idea to our schema we ended with two hypotheses.

The first hypothesis was that the existence of a significant proportion of biomass reused is a hallmark of an integrated land-use management that tend to increase the complexity and the number of habitats in agroecosystems. The second hypothesis was that the difference between NPP EROI and Final EROI could control whether a change in the energy throughput undermines or not the biomass available for other species. As we saw in section 1.2, it was not only non-cropland areas but also some of the low-intensity areas generated by traditional agricultures—the same areas that, at least in the Mediterranean, were and are being abandoned.

In our study cases, the difference between NPPEROI and Final EROI, decreased significantly in 1999 despite the proportion of the area being covered by forest, scrubland and pastures increasing. More specifically, the area of forest increased while the area known as *erial*, i.e. pastures and scrubland altogether, decreased.

By disaggregating between internal and external components of energy efficiency, we put forward the importance of the internal recycling of biomass, which is a component of the production process not considered in conventional Agricultural History. By doing so, we faced the main difficulty to build the energy profile of a historical agroecosystem, which is to find data. Some qualitative data is available, such as the opinions of the agronomists mentioned before or guidelines of management wrote by landowners (Garrabou et al. 2001a). However, the main available quantitative data are population census, manorial inventories, church tithes, parish and notary registers and cadastral sources.

2. Bloc 2. Nutrients flows in cropland area in the municipality of Sentmenat (Barcelona) c. 1860 and in the regions of Catalonia c.1920

In the second bloc, we dealt with the methodology and the interpretation of a balance of nutrients. We are aware that deficiencies in a nutrients balance, does not mean that the producing capacity of agricultural soils is depleted.This is because there are incorporations that are difficult to take into account, such as the mineralisation of soil nutrients stocks or deposition from the atmosphere. This was discussed some decades ago by Loomis (1978) for an agrarian system in the Middle Ages. Moreover it has been demonstrated by the few long run experiments of unfertilised plots, that yields drop to a minimum but can still can be harvested (Shiel 2010; Loomis et al. 2011). On the other hand, there are historical studies of increasing agricultural yields due to the increasing incorporations of convertible husbandry and leguminous rotations in England and North of Europe (Chorley 1981; Allen 2008). Like the reverse of a coin, in the American Great Plainscontinuous farming without the return of nutrients to the soil led to the loss of N stocks in soils (Cunfer 2004).

Nevertheless, we can take the replenishment of nutrients extracted in cropland areas as a proxy to the capability of the systems to increase fertility through their organic means. This is of outmost importance in areas with Mediterranean climates, because the summer drought reduces the flowering season of leguminous plants, thus shortening its cycle and limiting the densities of livestock that can be maintained. Some strategies were the concentration of nutrient replenishment in the more fertile lands,whereas other lands were almost non-fertilised. These lands still received nutrients through natural processes such as deposition and were sown by crops that could still produce with relative scarcity of nutrients. This ensued an overall disequilibrium in the balance of nutrients for the entire cropland area. This was the case of *ruedo* and the olive groves observed in the South of Spain (González de Molina 2002).

Something similar was concluded from the data collected c.1860 in Sentmenat (chapter 4).Vineyards were under-fertilised not because there were insufficient organic fertilisers but mainly due to the lack of access of many small winegrowers to livestock, pastureland and woodland. Still, the variety of fertilising methods was important for the overall balance (Tello et al. 2012).The advance of the vineyard frontier before the late nineteenth century turned viticulture into a cash crop exported to the emerging Atlantic economy. This entailed the expansion of cropland as well as a land-use intensification that put additional pressure on the replenishment of nutrients extracted from soil. The increasingly polarised and evolving agrarian world in Barcelona province c.1920 could no longer equilibrate their nutrient balances without resorting to chemical fertilisers. We deem that before the arrival of these industrial fertilisers a soil mining process had been in place, mainly in vineyards and perhaps other perennial crops like olives, almonds and nuts orchards.

From our case study c.1920 (chapter 5), we observed that wherever the environmental conditions and settlement patterns allowed pastures and cultivation of forages, the nutrients could be balanced, as was the case of the Pyrenees and Old Catalonia. When we disaggregated the Old Catalonia region, we found differences between the provinces of Barcelona and Girona. It was well known that Girona had significantly higher livestock densities than the other provinces (Pujol 1998). However, whereas the province of Girona had still a margin to increase yields by organic means, such was not the case of the province of Barcelona. From our balance c.1920, we know that the nutrients extracted could be returned by the combination of synthetic fertilisers to the organic ways already found for the province c.1860. Contrary to this situation, we found the case of New Catalonia, where the overall balance did not close even in combination with synthetic fertilisers. Although due to the scale of our sources, we cannot go into the details, from qualitative sources, we know that there was, again, an analogous situation to *ruedo* in the south of Spain. Most of synthetic fertilisers were used in high-investment crops such as rice and oranges (Calatayud 2006). But also, as long as the purchases of synthetic fertilisers were generalised, they increased in this area more than elsewhere (Garrabou et al. 1995). The area sown with forages grew in the province of Lleida in the first decades of the twentieth century together with the irrigated lands (GEHR 1991).

Although limited detailed information is available for Spain at the beginning of the twentieth century, our analysis reveals that using regional statistics entails comprehensive results, when administrative divisions include historical human settlements, geography and climate characteristics to define regions.

3. Combining nutrient and Energy balances c 1860. What can we learn? What questions can be made? The next step forward: can we combine the cases?

We have already discussed the problem of decoupling of scales due to the unavailability of data that we explained in chapter 6. Unfortunately, to integrate the two blocs of this thesis we would have needed a case study of energy flows c.1920 and a case study of nutrients flows in the croplands of an arid area c.1860.

In addition, we framed the analysis of both energy and nutrients flows mainly to cropland areas, thus consciously placing outside of our boundaries other important components of the agri-food system. For instance, it is possible to measure the flow of N that is released to water bodies due to the changes in the agri-food system, both from the sides of production and consumption (Lassaletta et al. 2009; Lassaletta et al. 2013b; Lassaletta et al. 2013a). This is especially relevant in Catalonia, as due to current imbalances in cropland, areas have increased the N pollution of groundwater (Penuelas et al. 2009; Hernández-Espriú et al. 2013). This affects the drinking water and it is of outmost importance in Mediterranean areas as water is a scarce resource (Lassaletta et al. 2013b). In addition, the inclusion of other compartments opens the door to solutions—to avoid leaching and pollution problems—beyond more effective applications of fertilisers in croplands that involve other actors and scales. In this case, lowering the consumption of animal protein would reduce the system's release of N while reducing external energy consumption (Smil 2001; Smil 2013; Lassaletta et al. 2013b).

At the beginning of the dissertation, we explained that according to the research project embedding in this dissertation, we distinguished between *driving* and *ruling* forces in agrarian change of territory. By driving forces, we meant those that were related with the socio-ecological domain, such as the energy or material flows and technical settings that operate these agrarian changes. By ruling forces, we mean those related with the socio-economic factors. These were mainly two, the institutional frame set up in each historical context, with their entitlement rules, that gave access to the different social groups to use natural resources or not. Second, the decision making processes which were in the hands of ruling classes, except for the counterbalance exerted by the powerless social groups either by their everyday resistance or by social revolts.

We centred the analysis on the driving forces and selected measuring the flows of energy and nutrients. We described some of the main ruling forces affecting the agrarian transition in Catalonia and we related them partially with these driving forces. As we stated at the end of chapter six, we do not know if the unbalances of nutrients found in the province of Barcelona and the New Catalonia regions c.1920 were due to population or to the inequality levels of the rural society. Relating the driving forces with the ruling forces of the agrarian transition in Catalonia is a stimulating task for future.

Something similar happens with ploughs, sewing machines and labour. Although they were included in the analysis of the energy flows, we included them just as another input in our model. The low productivity of labour of Spanish agriculture has been of major concern for Agrarian Historians (O'Brien and Prados de la Escosura 1992; Sudrià and Pascual 2002; Simpson 2003). Unluckily, in the study of the bio-physical driving forces, we did not integrate the productivity of labour,although some factors are embedded in our analysis. For instance, traditional fertilising practices used to be highly labour intensive, so not only machinery but also synthetic fertiliser, specialisation and use of less productive areasincreased labour productivity.

In addition, I think that considering labour would be an important step forward because it would shift our study from agricultural change to rural change. Indeed, non-agrarian labour in the form of a proto-industry embedded in the rural economy had strong weight in the development of Catalonia before the nineteenth century(Marfany 2010). Moreover, to include off-farm activities, formal and informal, was and still is important for the gendered structure of rural households in Catalonia (Narotzky 1990) and so for the configuration of rural metabolism. In addition, through mechanisation women were relegated to the least technologically sectors on the farm (Garcia-Ramon and Canoves 1988). We think that to integrate accurately the labour productivity in our analysis, both paid and unpaid, would be the next necessary step to integrate the ruling forces to the Socio-Ecological Transition in the northeast of the Iberia Peninsula. This stimulating proposal would be to include humans as funds releasing flows of different labour types just as has been done by studies of metabolism in rural systems (see for example Ariza-Montobbio et al., 2014; Scheidel et al., 2014). Undoubtedly, the combination of the driving forces with the ruling forces deserves more attention.

Finally, I would like to end by exploring the parting question of last chapter in order to link it with the historiographical debate about Spanish agriculture that we presented in the introduction. If yields were higher in more humid regions due to practices that allowed higher livestock densities, then, what was the non-industrial chance for arid areas such as the Lleida plains?

The low livestock densities per cropland area in dry-farming in the nineteenth century allowed it to say that the livestock and arable land were not integrated (Simpson 2003). As we mentioned elsewhere, the most important expert in Spanish dry-farming during the early twentieth century was the engineer José Cascón.He wrote about the importance of organic matter and described accurately the ploughing techniques to enhance water conservation within soils. He described as a pending issue the integration of rotations with leguminous crops in dry-farming conditions (Cascón 1913).

Cascón allowed the keeping of high livestock densities and high yields at this experimental farm. Nevertheless, Huguet del Villar explained in "*El valor geográfico de España*" at 1921 (Tello and Sudrià 2011) why it was not possible to reproduce the conditions of the farm of Cascón. The farm had some exceptional endowments such as groundwater that allowedit to irrigate one fifth of the cropland area. In addition, the proximity to railway and to the capital of the province allowed the sale of the products and the purchasing of fertilisers, machines and other inputs.Moreover, unlike most of the farms in the area, the lands of the farm were not scattered, but concentrated. Also, the high intellectual value and enthusiastic character of Cascón himself was unique. Finally, as an experimental farm, he had enough capital to invest in innovations and took risks.

Cascón himself agreed that for a normal farmer the maintaining of enough livestock densities was impossible because it was too costly. Still he thought that it was possible to increase the livestock numbers and he proposed two ways to cheapen the maintaining of livestock, to create temporary meadows and to plant trees (to have shadow pastures). With this, he was making an explicit criticism to the owners of the land. First, coinciding with the main thesis of the work of Huguet del Villar in 1921 (Tello and Sudrià 2011), about the excessive area sown with wheat, which went in detriment of forest and scrubland. Second, he accused the wealthiest Castillian landowners with enough means to maintain adequate livestock densities of neglecting this issue because they preferred to live off-farm. By doing so, he argued, theysecured their production only through the governmental tariffon wheat (Cascón 1914).

Both authors, Cascón and Huguet del Villar, defended *barbecho* as a way to store water in soils in order to reduce the risk of crop failure in dry years. Even considering the fluctuations of its results, it is still a widely used method to store water in soils used in dry-farming areas (Loomis et al. 2011).

Although his observations are qualitative, we can group them in three criticisms. The first one is the well known lack of integration of livestock and arable land in the interior of arid areas of Spain, already noticed by a number of historians (González de Molina 2002; Simpson 2003). Second, the lack of integration of humans and the arable land. He was concerned, as Liebig and Marx were in the nineteenth century, about the bottleneck of nutrient flows from human settlements. Like other agronomists at that time, he travelled to learn other practices. We know for sure that he visited the *Estación Enológica de Vilafranca del Penedès* in a winegrowing area of the province of Barcelona, and he was very impressed about how they managed the organic matter. He presented this praise to the Catalan farmers: "*Hay un depósito permanente, de gran importancia, escaso y muy mal aprovechado en general a excepción de Cataluña, que es la basura de todas clases de los centros de población, que siendo en general la más rica en elementos nitrogenados, va a perderse por el alcantarillado, con gran perjuicio de las poblaciones ribereñas, en los ríos próximos a las mismas*" (Cascón 1918). However, we do not know if this quote was referring to Catalonia as a whole, including the arid plains of the province of Lleida,or only the farms that he visited. Third, the homogenisation of the landscape in favour of large, uninterrupted wheat cropland areas.

Are these three criticisms far from what agroecologists recommend today? I deem that by studying the main ruling forces that blocked the integrated management of these past arid agroecosystems we can have valuable information for the present. In addition, to what extent was the narrative of modernity imposed over other possibilities? We know that this happened with the prevalence of the discourse about the expansion of irrigation together with the building of big dams (Swyngedouw 1999). Could the same have happened over the integrated management of organic matter and landscape management?

If so, the results of this PhD Thesis open a wide research agenda to identify the factors that might have blocked a better integration between humans, land and livestock in Iberia. A question that will undoubtedly come up again in our near future in a post-oil era.

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