Widening the analysis of Energy Return On Investment (EROI) in agro-ecosystems: socio-ecological transitions to industrialized farm systems (the Vallès County, Catalonia, c.1860 and 1999)

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Energy balances of farm systems have overlooked the role of energy flows that remain within agro-ecosystems. Yet, such internal flows fulfil important socio-ecological functions, including maintenance of farmers themselves and agro-ecosystem structures. Farming can either give rise to complex landscapes that favour associated biodiversity, or the opposite. This variability can be understood by assessing several types of energy returns on investment (EROI). Applying these

measures to a farm system in Catalonia, Spain in 1860 and in 1999, reveals the expected decrease in the ratio of final energy output to total and external inputs. The transition from solar-based to a fossil fuel based agro-ecosystem was further accompanied by an increase in the ratio of final energy output to biomass reused, as well as an absolute increase of unharvested phytomass grown in derelict forestland. The study reveals an apparent link between reuse of biomass and the decrease of landscape heterogeneity along with its associated biodiversity.

List of acronyms: EROI: Energy Return On Investment. GCV: Gross Calorific Value. NPP: Net Primary Productivity

1. Introduction

Agro-ecosystems are nature transformed by humans (González de Molina and Toledo, 2011; Haberl et al., 2004). When farmers invest labour, animal draught power, mechanical work, seeds, fertilisers and other energy carriers, they create a new cultural landscape from the existing ecosystem (Odum, 2007). Their creation and maintenance requires continuous investment of energy and information by human society, in addition to naturally occurring solar radiation and photosynthesis (Altieri, 1989; Gliessman, 1998). Although present agriculture relies on fossil fuels, food production will always depend on ecosystem services closely linked to biodiversity, such as fresh water, pollination, biological pest control, N fixation, etc., which cannot be substituted by technical capital (Giampietro, 1997).

Economic analyses of agriculture not only dismiss the role of fossil fuels in agriculture, due to their low relative price, but also overlook the non-marketed energy flows of internal biomass reuses and the role that unharvested biomass plays for non-domesticated species (Martinez-Alier, 1997). An assessment of Energy Return on Investment (EROI) (Hall, 2011) measures the energy efficiency of an energy-gathering system. Expressed as a ratio, EROI compares a system’s energy output to its energy input. As long as modern agriculture depends on fossil fuels for its largest energy input, the world food supply remains vulnerable to an eventual reduction in oil supplies (Campbell and Laherrère, 1998; Deffeyes, 2001). Understanding the energy efficiency of agricultural systems is important, whether oil’s ultimate decline results from depleted supplies or from voluntary reduction in the face of climate change (Arizpe et al., 2011; Giampietro et al., 2013; Hall, 2011; Murphy and Hall, 2011; Scheidel and Sorman, 2012).

Some studies have addressed the energy accounts of agricultural systems (Balogh et al., 2012; Bayliss-Smith, 1982; Campos and Naredo, 1980; Conforti and Giampietro, 1997; Giampietro et al., 2013, 1994, 1992; Leach, 1976; Odum, 1984; Pimentel and Pimentel, 1979; Pracha and Volk, 2011). While they all account for labour, fossil fuels and embodied energy in fertilizers, pesticides and machines, only those addressing pre-industrial agriculture take into account energy flows generated and also consumed within the agro-ecosystem. Examples include self-produced feed and straw for livestock and other energy carriers related to local fertility management practices. These internal energy flows are not normally accounted in monetary terms, nor do they appear in official farm statistics, making them difficult to quantify. However, internal energy loops were very important in past organic farm systems that used little or no fossil fuels (González de Molina and Guzmán, 2006; Naredo, 2004; Tello et al., 2012). Remembering that agriculture's main purpose is to produce food, fibre and fuel, an assessment of agriculture's energy efficiency in a scenario without fossil fuels requires acknowledging the multifunctionality of past agrarian systems. How much of the biomass produced was reused within the system? What other products did farmers extract from non-cultivated areas of the farm system?

This paper compares a past organic[1] farm system that did not use fossil fuels with one today that utterly depends upon them. Doing so requires taking into account internal flows usually neglected in EROI assessments of modern farm systems. Performing a wider comparison of the energy profiles of organic and industrial farms systems necessitated the development of a set of several different EROIs, instead of a single one. We based these EROIs in an empirical case study that presents these EROIs for the farm systems in four villages of the Vallès County in Catalonia, Spain, in 1860 and 1999 (Tello et al., 2016).

Vallès County had a higher EROI in 1860 than in 1999, as expected, and the wider analysis revealed two contrasting strategies, one relying on biomass reused (in 1860) and the other on

[1] In this paper, we use the term "organic" in the sense introduced in the classical work of Wrigley (1988) to distinguish land-based energy economies from fossil fuel-based energy economies.

external inputs (in 1999). These external inputs were mainly livestock feed imports to sustain the present specialisation in feedlot meat production, which is tightly linked with a global agri-food system that depends on the availability of cheap fossil fuels.

Section 2 introduces the case study location, describes agro-ecosystem energy inputs and outputs, and explains the EROI formulas. Section 3 presents the EROI results for this case study. Section 4 discusses those results while Section 5 outlines some general conclusions and opportunities for future research.

Figure 1. Map of land use in the four Vallès County villages, c. 1860 and 1999

INSERT FIGURE 1 HERE

Source: from Marull et al. (2016)

2. Case study description, concepts and methods

2.1 Sources and description of the case study

The Vallès County study area is a small plain situated in a tectonic basin between Catalonia's littoral and pre-littoral mountain ranges in northeastern Spain. Its diverse geological substrata and precipitation above the Mediterranean average (600-800mm) created a considerable variety of soils with a broader range of agricultural possibilities than in drier parts of the country (Olarieta et al., 2008). The area has always been well-connected to Barcelona, just 35 kilometers to the south, and its commercial and demographic dynamics, even in the nineteenth century when the trip took between 5 and 12 hours on horseback (Cussó et al., 2006a).

The data for this study comes from four villages in Vallès County: Sentmenat, Palau-solità-i-Plegamans, Caldes de Montbui and Castellar del Vallès (Figure 1). For previous research about the area, see Cussó et al. (2006a, 2006b), Marco et al. (Forthcoming) and Tello et al., 2015.

Figure 2. Land uses in four Vallès County villages, c. 1860 and 1999

INSERT FIGURE 2 HERE

Note:'Other' in 1860 are irrigated crops, olive groves, horticultural land and fruit trees, while in 1999 'other" includes potato fields as well. Total area: 12,398 ha. Source: data collected from the cadastral records in the Archive of the Crown of Aragon (ACA), concerning the municipalities of Caldes de Montbui, Castellar del Vallès, Palau-solità i Plegamans and Sentmenat in the 1860s. For 1999-2004, data come from the Rural Cadastral Service of the Province of Barcelona and IDESCAT statistics (http://www.idescat.net/en/).

From 1860 to 1999 forest and scrubland increased to 55% and cropland decreased by 67% (Figure 2). The main crop cultivated in 1860 was vineyards, which, after the Phylloxera plague, had almost disappeared by the beginning of the twentieth century (Tello and Badia-Miró, 2011). Built up and agriculturally unproductive area had increased by an order of magnitude in 1999 due to urbanization. Grassland occupied little area in 1860, as was typical in Mediterranean regions, but decreased to even less in 1999 with the reduction of grazing livestock such as sheep (Table1).

Table 1. Characteristics of Vallès County farm systems, c.1860 and 1999

INSERT TABLE 1 HERE

Notes: * 62% of agricultural workers in 1999 were family members without formal salary. **From draft animals. Transhumant sheep stayed only half a year within the system. Source: Tello et al. (2015) and Marco et al. (forthcoming).

Draft animals, which were the only source of motive power on farms in 1860, had almost disappeared by 1999. Livestock densities in the nineteenth century were lower than elsewhere in Europe (Krausmann, 2004) and insufficient to provide the manure required to fertilize cropland. Therefore, peasants had to rely on a variety of other fertilizing methods (Tello et al., 2012). In 1999, total livestock had increased 26 times over due to the concentrated swine feedlots. There were twice as many swine as people, even though the human population had increased by five times.

2.2 System boundaries

The boundaries of the agro-ecosystem encompass all land suitable for terrestrial plants in the four municipalities. This includes cropland, grassland and forest and scrubland. It does not include built up (urban) land. Except for sunlight, farm operators control all inputs, outputs and internal loops of energy. A more detailed discussion about various system boundaries and their conceptual implications can be found in Tello et al. (2015).

Figure 3. System boundaries and modelling of energy flows applied to a Catalan agro-ecosystem c. 1860 and 1999

INSERT FIGURE 3 HERE

Notes: 1: Human Labour. 2: Humanure, human garbage and sewage. 3: Embodied energy to produce machines. 4: Fuel to run machines and electricity. 5: Embodied energy in herbicides and pesticides. 6: Embodied energy in mineral fertilizers. 7: Seeds. 8: Embodied energy of external feed. 9: Biomass burnt and ploughed into cropland. 10: Seeds generated within the system and other buried biomass like stubble, green manure, pruning, etc. 11: Biomass diverted towards livestock. 12: Final Produce. 13: Livestock Barnyard Produce (LBP). 14: Net Primary Productivity harvested. 15: Unharvested Phytomass. AcBiom: Acumulated biomass. The energy flows that cycle again into the agro-ecosystem suffer a number of secondary processes, e.g. burnt, storaged in the form of accumulated biomass, move between trophic levels, transformed into work or heat, etc. These processes, together with the losses are depicted in the figure but not explained in the text, as they are not under the scope of the study. Graph created with EmSim software.

2.3 Energy Inputs

Gross Calorific Values (GCVs) from Guzmán et al. (2014) account for all biomass energy carriers coming from the Net Primary Productivity (NPP) taking place either within or outside the boundaries of the system. Non-biomass inputs include energy embodied within their production and transportation (Guzmán et al. 2008).

Energy from sunlight does not appear as an external input because farmers do not control it. Besides, as one of the justifications for an energy assessment of agriculture is the depletion of fossil fuels, it is out of scope of this article to address sunlight.

2.3.1 External inputs

External Inputs include all agro-ecosystem inputs coming from outside the system boundaries (Table 2). Labour is accounted by the fraction of the average diet of the farm operators that corresponds to their agricultural work time, estimated by taking physiologically different energy requirements for various types of work into account. The calculation considers the local or external origin of their food baskets, accounting direct Enthalpy values in GCVs in the former case, and adding the embodied energy cost of transport and delivery in the latter case (Aguilera et al., 2015; Marco et al., Forthcoming). This labour accounting relies on what Fluck (1992) 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 (Tello et al. 2015). In contrast to peasant labour, slave labour would have to be regarded as an internal flow of the agro-ecosystem. Slaves were sustained by landowners only as a means of production similar to draught animals, or *instrumentum vocale* ("tools that speak") as the ancient Romans termed it.

Like in many pre-industrial farm systems around 1860, External Input had no fossil fuel components; domestic residues, human labour and humanure were the only inputs. By 1999, in contrast, the main External Inputs were imported animal feed, the embodied energy in that feed, electricity consumption, machines and fuel.

Table 2. External inputs in the Vallès County farm system in energy units

INSERT TABLE 2 HERE

All external inputs are accounted as their GCV added to their embodied energy if they were not biomass.*Due to rounding some totals may not add up perfectly. Source: Tello et al. (2015) and Marco et al. (forthcoming).

2.3.2 Biomass Reused

Biomass Reused (BR) represents energy carriers harvested from Farmland that are reinvested into the agro-ecosystem instead of being diverted towards Final Produce—e.g. seeds, feed and fodder (when they are not brought from outside the system), green manures, and grass grazed in grassland by livestock. Some fractions of forest biomass removed from forest and scrubland are reused in cropland (as litter or branches ploughed into cropland either fresh or burnt) or by livestock (like acorns grazed or shrubs used as bedding in stalls). Buried biomass used as cropland fertilizer had an important weight in energy terms in 1860 (Table 3), whereas most Biomass Reused in 1999 went towards livestock.

Manure and animal work are not part of Biomass Reused to avoid double counting of energy flows. Otherwise, they would be accounted first as cropland produce and a second time after having passed through the livestock subsystem. Hence, they have no numerical value in Figure 3, although the energy flow from livestock to farmland is represented. Even though they do not contribute directly to the EROI assessment, they connect to External Inputs since managing manure and using draught animals require human labour.

In the existing scholarly literature, attempts to include Biomass Reused in EROI analysis have been problematic due to the double nature of reuses (input and output at the same time), as Carpintero and Naredo (2006) explained when they tried to compare EROIs obtained in several studies of past and present farm systems in various regions of Spain. What's more, inconsistent methodologies make it difficult to compare case studies.

Table 3. Biomass Reused in the Vallès County farm system in energy units

INSERT TABLE 3 HERE

*Due to rounding some totals may not add up perfectly Source: Tello et al. (2015) and Marco et al. (forthcoming).

2.4 Energy outputs

The output of the system, Final Produce (FP), is the net supply of energy carriers in a suitable form for human consumption or use, whether locally or afar. Firewood from cropland and forest and scrubland had an important weight in energy units in 1860 (Table 4), whereas in 1999 the most important output was edible animal products in accordance with the livestock feeding specialization. The energy flow Livestock Barnyard Produce (LBP), e.g. meat, dairy, carcasses, etc., is a sub-flow of Final Produce and it corresponds to number 13 in Figure 3.

Table 4. Final Produce in the Vallès County farm system in energy units

INSERT TABLE 4 HERE

*Due to rounding some totals may not add up perfectly. Source: Tello et al. (2015) and Marco et al. (forthcoming).

2.5 A single EROI is not enough: A set of four EROIs

2.5.1 Final EROI

Most EROI analyses only relate external inputs (direct and embodied energy) with the energy consumption derived *in situ* from the final output (Murphy et al., 2011). Final EROI assesses instead the energy investment made by farmers and the society they belong to in exchange for a basket of human consumable biomass products accounted in energy terms. It is equivalent to $EROI_{soc}$ in Hall et al. (2009) or to "standard EROI", Murphy et al. (2011). Final EROI assesses how much external (direct and indirect) and internal (direct) energy a farm-operator invests to achieve a given output.

$$Final\ EROI\ (or\ FEROI) = \frac{Final\ Produce}{External\ Inputs + Biomass\ Reused} \qquad \text{Eq. 1}$$

2.5.2 External Final EROI

External Final EROI excludes the energy produced and then consumed within the system. Murphy et al. (2011) called it the *External Energy Ratio*. This ratio assesses to what extent the agro-ecosytem analysed becomes either a net provider or a net consumer of energy in its connection with the broader societal system. Carpintero and Naredo (2006) review the use of this measure for historical comparisons of farm systems in various regions of Spain.

$$External\ Final\ EROI\ (or\ EFEROI) = \frac{Final\ Produce}{External\ Inputs} \quad \text{Eq. 2}$$

2.5.3 Edible Energy Efficiency

Edible Energy Efficiency (EEE) is a variation of External EROI. It assesses the dependence of food production on fossil fuel and the evolution on energy efficiency at the end of the twentieth century, taking into account direct and embodied energy in external inputs (Balogh et al., 2012; Hamilton et al., 2013; Pracha and Volk, 2011).

$$Edible\ Energy\ Efficiency = \frac{Edible\ Final\ Produce}{External\ Inputs} \quad \text{Eq.3}$$

2.5.4 Internal Final EROI

Internal Final EROI assesses the portion of Land Produce intentionally returned to the agro-ecosystem (i.e., Biomass Reused), in order to obtain a unit of consumable Final Produce. This indicator has the potential to distinguish solar- and fossil fuel-based agricultural systems because of the changing role of Biomass Reused.

$$Internal\ Final\ EROI\ (or\ IFEROI) = \frac{Final\ Produce}{Biomass\ Reused} \quad \text{Eq. 4}$$

2.5.5 NPP_{act} EROI[2]

NPP_{act} is the total phytomass available to sustain humans as well as all other heterotrophic species. Species not directly managed by people and the ecosystem services they provide are affected by the flow of energy and information that farmers invest. Unharvested Phytomass

[2] This indicator uses the nomenclature of HANPP calculations, where NPP_{act} refers to the actual vegetation. See below.

(UPH) represents the share of total production of the agro-ecosystem that remains available for self-reproduction. Unlike the previous measures, NPP_{act} EROI expresses energy return in terms of the total phytomass obtained through the photosynthetic conversion of solar radiation in the agro-ecosystem (Guzmán and González de Molina, 2015).

$$NPPact\ EROI\ (or\ NPPEROI) = \frac{\text{NPPact}}{EI+BR} \quad \text{Eq.5}$$

Where $\text{NPP}_{act} = UPH + BR + FP - LBP$, UPH: Unharvested Phytomass, FP: Final Produce; LBP: Livestock Barnyard Produce; EI: External Inputs; BR: Biomass Reused.

NPP_{act} does not constitute an energy output because its flow does not cross the system boundary. Estimation of NPP_{act} follows the method used to assess Human Appropriation of Net Primary Productivity (HANPP), an aggregated indicator that reflects both the amount of area used by humans and the intensity of land use (Haberl et al., 2013).

$$HANPP = NPP_0 - NPP_t \quad \text{Eq. 6}$$

where,

$$NPP_t = NPP_{act} - NPP_h \quad \text{Eq. 7}$$

HANPP: Human Appropriation of Net Primary Productivity; NPP_0: amount of NPP that would be available in an ecosystem in the absence of human activities; NPP_t: amount of NPP that actually remains in the ecosystem, e.g. the vegetation remaining in agro-ecosystems after harvest; NPP_{act}: actual vegetation under prevailing land covers; and NPP_h: amount of NPP harvested by humans.

Thus, the harvested biomass is the phytomass extracted by people from cropland, pasture and forest and scrubland. This is slightly different from the NPP_h used in HANPP assessments, which includes unused components of the plant that are not actually extracted but remain in the agro-ecosystem, e.g. biomass destroyed during harvest, which appears here as Unharvested Phytomass potentially available for associated biodiversity.

$$\text{NPPh} \approx LP = BR + FP - LBP \quad \text{Eq.8}$$

LP: Land Produce; FP: Final Produce; LBP: Livestock Barnyard Produce.

A modified version of NPP_t corresponds with Unharvested Phytomass (UPH). Then,

$$NPPt \approx UPH = NPP_{act} - NPP_h \quad \text{Eq. 9}$$

Estimating NPP_{act} requires calculating NPP_h for each category of land use. For cropland, this means the energy contained in the primary products (e.g. wheat grain, olive oil, grape juice) and in by-products (see Tables 5 and 6). The NPP_{act} value of fallow land (where there is neither NPP_h nor losses) is estimated to be the same as in pastures.

Table 5. Data to calculate the NPP_h of cropland in the Vallès County farm system, c.1860

INSERT TABLE 5 HERE

*Total area may not coincide with table 2 as is not the sum of the areas of all crop types due to more than one harvest per year in some cases, as well as inter-cropping within olive groves. NPP_h: Net Primary Productivity harvested, GCV: Gross Calorific Value. Harvest includes the main marketable product from crop types before being processed, e.g. grape juice (to make wine). By-products are the part of the crop plant that was also collected but was not the main goal (and so its appearance in statistics is not always clear), e.g. prunings from vineyards and grape pomace. Source: Tello et al. (2015) and Marco et al. (Forthcoming).

Table 6. Data to calculate the NPP_h of cropland in the Vallès County farm system in 1999

INSERT TABLE 6 HERE

NPP_h: Net Primary Productivity harvested, GCV: Gross Calorific Value. Harvest includes the main marketable product from crop types before being processed, e.g. grape juice (to make wine). By-products are the part of the crop plant that was also collected but was not the main goal (and so its appearance in statistics is not always clear), e.g. prunings from vineyards and grape pomace. Source: Tello et al. (2015) and Marco et al. (Forthcoming).

Unharvested Phytomass in cropland includes weeds and the part of the harvest eaten by pests and other herbivores. Oerke et al. (1999) provides potential and real loss values for wheat, barley, corn, potatoes and soybeans at a large regional scale. This estimation uses “real” values for 1999 and the lowest value of “potential” losses for 1860.

Estimations of weed production come from Guzmán et al. (2014) except for alfalfa in 1860, which employ values from organic forage (Sheaffer et al., 2014) and in 1999 from conventional farming using the herbicide Lamazox (Bradley et al., 2010).

As there is not a complete match between available land use and crop area data in 1860 and 1999, different land use categories are aggregated in order to produce comparable groupings valid for both 1860 and 1999. For instance, separate categories for citrus trees and other kinds of fruit are summarized simply as "fruit trees".

Table 7. NPP_h in forest and scrubland and grassland in the Vallès County farm system c.1860 and 1999

INSERT TABLE 7HERE

NPP_h: Net Primary Productivity harvested, GCV: Gross Calorific Value. Source: Tello et al. (2015) and Marco et al. (Forthcoming).

The NPP_{act} from grassland and forest and scrubland includes the annual biomass production of *Brachypodium retusum* from GN (2012) and Olea (2010) in grassland (1440 kg DM/ha) and forest and scrubland (1000 kg DM/ha). Timber and firewood (958.47 kg DM/ha) from forest and scrubland are the values for Catalonia from Puy et al. (2007) and from the wood production tables (Gonzalez and Ibariz, 1998; Montero, 2004; Montero et al., 2000; Vericat et al., 2012). These estimates do not include belowground biomass as few studies that assess this component.

Table 8. NPP_{act} of cropland in the Vallès County farm system, c.1860

INSERT TABLE 8 HERE

NPP_{act}: Net Primary Productivity of actual vegetation, NPP_h: Net Primary Productivity harvested, UPH: Unharvested Phytomass. Source: Tello et al. (2015) and Marco et al. (Forthcoming).

Table 9. NPP_{act} of cropland in the Vallès County farm system, 1999

INSERT TABLE 9 HERE

NPP_{act}: Net Primary Productivity of actual vegetation, NPP_h: Net Primary Productivity harvested, UPH: Unharvested Phytomass. Source: Tello et al. (2015) and Marco et al. (Forthcoming).

3. Results

3.1 Energy Return on Investment

The list of energy efficiencies in table 10 shows the great changes in energy terms over the course of a century and a half. Final EROI, i.e. the ratio of output to external inputs and biomass reused, decreased by 79% between 1860 and 1999. With only the external inputs included in the denominator (External Final EROI), the decrease was sharper, by 99%, which is reasonable since there was no external feed in 1860. The decrease is by 95% if we take into account only the edible output. The Internal Final EROI, i.e. the ratio of output to internal inputs or biomass reused, increased by 51%, which is reasonable since farm operators re-used less biomass and produced a larger output in 1999.

The NPP_{act} EROI, which is the ratio of net primary productivity of the actual vegetation to external inputs and biomass reused, decreased by 82%.

The efficiency of labour decreased by almost 100% from 1860 to 1999, however it increased by six times accounting only the edible outputs. This large difference is due to the importance of firewood in 1860.

Table 10. EROIs obtained in the villages of the Vallès County, c.1860 and 1999

INSERT TABLE 10 HERE

FP: Final Produce, EI: External Inputs, BR: Biomass Reused, NPP_{act}: Net Primary Productivity of the actual vegetation, UPH: Unharvested Phytomas, L: Labour.

3.2 Harvested and unharvested Net Primary Productivity

In absolute terms actual Net Primary Productivity (NPP_{act}) did not change between 1860 and 1999 in Vallès County (Table 12), however, it increased by 24% on a per hectare basis (Table 11). This is because the significant amount of land given over to urban development reduced photosynthetically active land covers by 20%. Net Primary Productivity harvested (NPP_h) from all land use types decreased by 43% on a per hectare basis in 1999, however these dynamics were different depending on the land use category. NPP_h from cropland doubled in 1999, but it decreased by 80% and by 92% from grassland and forest and scrubland respectively. Hence, whereas in 1860 cropland NPP_h was almost as important as that harvested from forest and scrubland, by 1999 cropland NPP_h represented 93% of all NPPh.

Unharvested phytomass (UPH) from cropland decreased by 27%, but increased by 140% for all land uses. Grassland UPH increased more than fourfold, although it hardly affects the total results since by 1999 most former grassland had become forest and scrubland. Thus, the increase of UPH mainly occurred in forest and scrubland.

Table 11. Values of NPP_h, NPP_{act} and UPH estimated in the Vallès County farm system, c.1860 and 1999

INSERT HERE TABLE 11

NPP_h: Net Primary Productivity harvested, NPP_{act}: Net Primary Productivity of actual vegetation, UPH: Unharvested Phytomass. UPH was calculated according to Eq.9.

Table 12. Net Primary Productivity in energy units in the Vallès County farm system, c.1860 and 1999

INSERT TABLE 12 HERE

$NPP_{h:}$ Net Primary Productivity harvested, NPP_{act}: Net Primary Procductivity of actual vegetation, UPH: Unharvested Phytomass. *Due to rounding some totals may not add up perfectly.

4. Discussion

4.1 Comparison of a farm system in 1860 and 1999

Although in 1999 the Final Produce increased by 20%, Final EROI dropped because of a fivefold increase of the total farmland inputs. There were significant changes in the composition of Final

Produce (FP). First, the wine-wheat farm system of 1860 changed to a meat production system by 1999, including an increase in feedlot-based meat production from 1% to 76% of Final Produce. The efficiency of edible output to labour had increased by 1999 compared with 1860, although the product (meat as opposed to wine and wheat) is completely different in nutritional values and price.

Second, cropland produce increased in cereals and leguminous crops used for livestock feed by 1999. Nevertheless, this was not enough to cover the needs of livestock, and only met 13.3% of feed requirements from locally production. The rest of the feed supply, some 86%, had to be imported from overseas along supply routes that averaged nearly 6,000 km. Indeed, feed imports were the main cause (76%) of the increase in External Inputs by 103 times. Competition between human food and livestock feed represented a typical limitation of pre-industrial farm systems. However, specialization on meat production by 1999 was now possible because the farm system had become embedded in a global agri-food production system reliant on fossil fuels, which eliminated the human-livestock food competition and dramatically expanded the system's feed production capacity as well.

Third, forest and cropland total produce decreased. The domestic use of firewood as fuel had almost disappeared by the end of the twentieth century, substituted by fossil fuels for heating (Figure 4). Gas consumption as domestic fuel is outside this model's system boundaries, so this account only considers the minor extractions from forestland. Together with forest firewood, farm, operators used wooden prunings as fertilizer, burned locally on fields locally in "*formiguers*" in the nineteenth century (Olarieta et al., 2011). This ancient practice, once common in the Iberian Peninsula, was highly labour intensive and had almost disappeared by the second half of the twentieth century (Miret, 2004).

Figure 4. Primary energy of annual domestic fuel consumption in Spain

INSERT FIGURE 4 HERE

Notes: Modern energy is coal, gas and oil. Firewood includes pruning from wooden crops. Source: modified from Infante-Amate et al. (2014).

Firewood was 82% and 8% of final produce in energy terms in 1860 and 1999 respectively. Despite firewood's large share of final produce in 1860, it is not reasonable to compare quantitatively the values of firewood energy and edible energy because they serve very different functions for farmers. This apparent inconsistency is a limitation of the methodology. Nevertheless, this result demonstrates the important fuel-supply function of multi-functional pre-industrial farms. They provided society not only with essential food, also with fuel for domestic heat.

4.2 Comparison with other EROIs in agriculture

The decreasing pattern in Edible Energy Efficiency contrasts with others found in the literature. Hamilton et al. (2013) found a dramatic increase of the United States EEE from 1970 to 2000 and a steady state in the following decade, whereas for Canada EEE remained stable between 1980 and 2010. Pracha and Volk (2011) found a decrease of EEE from 1999 to 2005 for rice and wheat in Pakistan, followed by four years of increases for rice (while wheat showed no clear pattern). This lack of uniform result arises from incompatible comparisons. Hamilton et al. (2013) compared farm systems that were already industrial while Pracha and Volk (2011) compared two single crops at the country level. This study, on the other hand, compares a pre-industrial and a modern farm system at the regional level. The specialization in meat feedlot production in Vallès County explains the sharp decrease in EEE. First, there was a decrease in EEE because of the inefficiency of livestock energy conversion (feed grains into meat) and second because of the large amounts of energy embodied in feed imported from overseas.

Evaluating EEE by taking only human labour as the input (Table 10) makes the 1999 system appear more efficient than that of 1860. This is the typical result found when studying the transition from traditional to modern modes of agriculture since the use of fossil fuels increased labour productivity at the cost of energy efficiency (Krausmann, 2004).

Carpintero and Naredo (2006) reviewed the studies on energy efficiency of agriculture for various regions of Spain in different years. They found that authors treated Biomass Reused in different ways, so instead of comparing Final EROI it makes more sense to compare External Final EROI, i.e. the ration of Final Produce to External Inputs. The trend and the magnitude of

Final EROI is similar to the trends found by the studies that compare "traditional" agriculture with "modern" agriculture in Andalucia, in southern Spain (from 37 to 2.43) and Asturias in northern Spain (from 15 to 0.37). Guzmán and González de Molina (2015) found an External Final EROI of 9.42, 11.01 and 2.18 for the village of Santa Fe in Andalucia for the years 1752, 1904 and 1997 respectively. The rest of the studies were for the second half of the twentieth century and showed similar External Final EROIs as in Vallès County in 1999. Despite considerable regional variability within Spain, the industrialization of agriculture followed a similar trend of decreasing external energy efficiency. In the late twentieth century External Final EROI was higher in Andalucia than in Catalonia. This could be due to the high yields of the particular villages studied, as explained with the NPP_{act} EROI, or because of the difference between crop production and meat production systems.

The NPP_{act} values in Vallès County followed the same trend as those described for southern Spain in 1752, 1904 and 1997 for cropland, grassland and forestland (Guzmán and González de Molina, 2015). Values presented here are about 50% less per hectare because they do not take into account belowground biomass. NPP_{act} EROI, however, did not follow the same trend, as it increased in southern of Spain. The authors attributed that increase to more biomass from cropland produced by the higher yields resulting from irrigation and the introduction of new crops with higher biomass production, such as sugar beet and poplar, a significant difference from Vallès County.

Internal Final EROI, i.e. the ratio between output and internal inputs or biomass reused, increased from 1.08 in 1860 to 2.20 in 1999, meaning that in the nineteenth century the lack of External Inputs was compensated by an intensive use of Biomass Reused. Internal biomass flows went mainly toward fertilizer and to maintain livestock, which in the interim provided draught power and manure (although these energy flows do not contribute to EROI in order to avoid double-counting a fraction of their energy flow). Hence, in 1860, 0.9 units of biomass reused were necessary to get one unit of Final Produce from the agro-ecosystem; in 1999 only half as much was necessary.

4.3 Importance of other energy flows not included in EROIs.

In 1999, part of the biomass potentially reusable became "waste", e.g. stubble burnt on the fields and manure slurry accumulated in pools, as its production overwhelmed the absorption capacity of nearby fields and created problems of water and air pollution. To quantify these wastes or losses from livestock, it is necessary to estimate the excess of slurry, either stored or leached, after closing the nitrogen cycle of cropland at the municipality scale. The correspondence of these waste flows in Figure 3 are the losses from the Plants bullet and Livestock hexagon. They went from 0 in1860 to 11,150 GJ in 1999. These losses are not accounted in the EROIs and therefore do not modify the results. However, acknowledging them is meaningful since this biomass is nowadays discarded because of the extinction of some labour-intensive peasant practices (extraction and reallocation of biomass in order to fertilize cropland) and spatial disintegration of livestock from farmland.

Finally, there are studies at different regional scales that are nearby or contain the Vallès study area (Otero et al., 2015; Sirami et al., 2008; Tello et al., 2014; Zamora et al., 2007) that relate grazing and charcoal production with the endangerment or simplification of species communities. These practices, together with a more heterogeneous cropland area, created a new agricultural landscape mosaic (Marull et al., 2010). Towards the end of the twentieth century, when they were not built up into urban areas, abandoned pastures and cropland changed to forest through ecological succession. These changes contributed to higher biomass accumulation, as well as homogenization of forest covers, intensifying the wildfire regime (Cervera et al., forthcoming).

5. Concluding remarks

The Vallès County farm system in 1860 was a non-fossil fuel agro-ecosystem producing wine for market and wheat for self-consumption and supporting low livestock densities. By 1999, it had become a farm system oriented towards the production of meat in feedlots integrated into a global agri-food system, one possible only due to the availability of cheap fossil fuels.

A single EROI is not enough to compare the energy profiles of agro-ecosystems of past and present times. This is true in the first instance because an important share of energy flows driven by farm-operators re-cycles through the agro-ecosystem as biomass reused. Second, the final produce contains non-equivalent energy types that have different functions (i.e. edible and nonedible products). In the past, the extraction of firewood from cropland and forestland was an important economic output of farm systems. These two energy flows, biomass reused and firewood, were negligible in 1999. Hence, the set of EROIs presented here provide a more comprehensive representation of changing agro-ecosystems.

NPP_{act} EROI has related usefully three characteristics of the Vallès County farm system transition towards a fossil fuel based agro-ecosystem: the absolute increase of Unharvested Phytomass, the absolute decrease of harvested Net Primary Productivity (possible due to the integration into the global agri-food system) and the decrease of Final EROI.

This EROI assessment misses some information, such as losses or wastes that appeared in 1999. This flow is important for understanding pollution problems derived from high livestock density in feedlots, but does not affect the EROI assessment.

Further investigation is needed to link biomass reused with the structure of the land cover mosaic, which can increase the number of habitats and ecotones in an agro-ecosystem, enhancing biodiversity. Further studies should investigate the missing link between lost agricultural practices and the decline of some species in Mediterranean areas at a landscape scale.

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Figure 1

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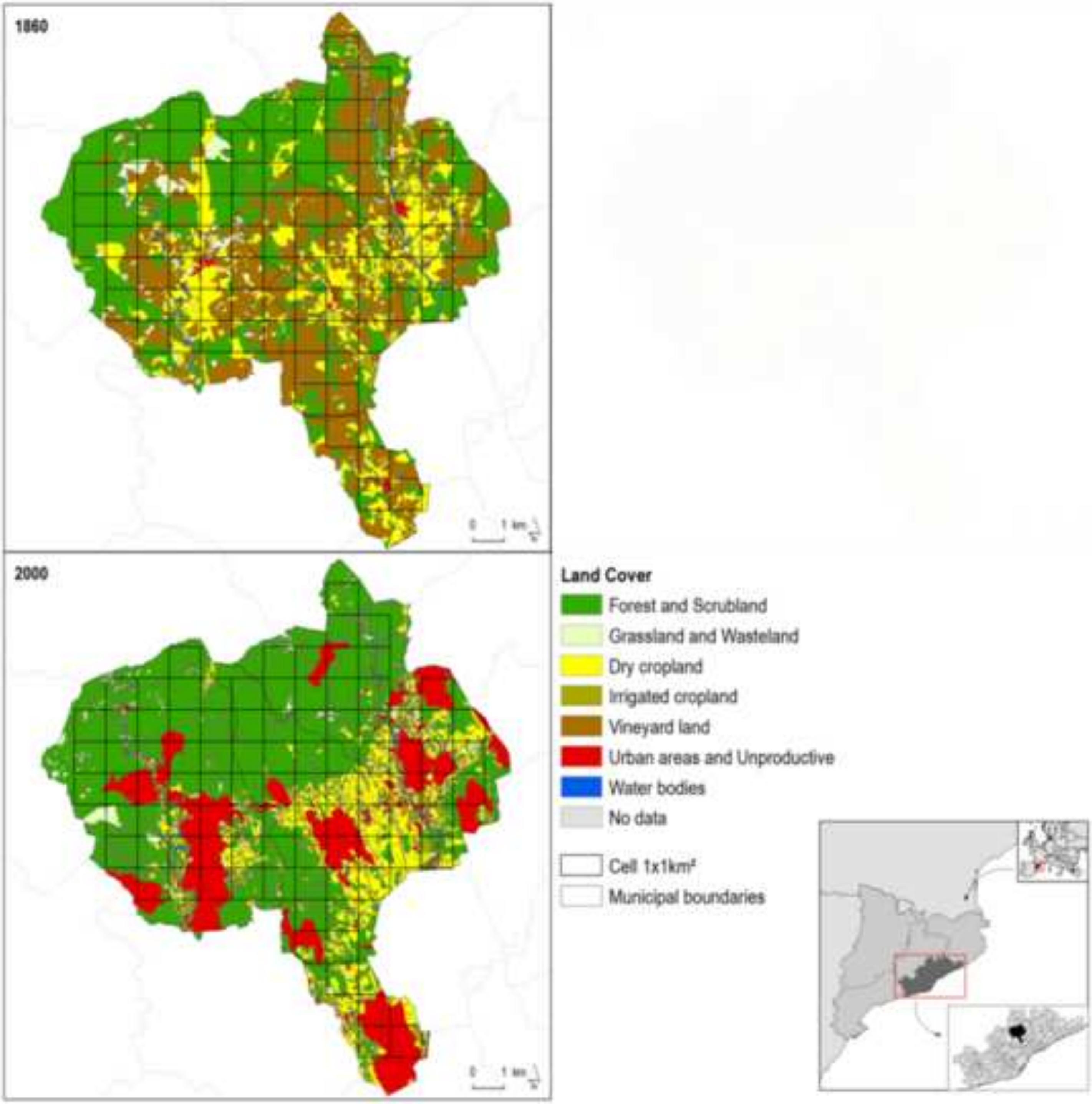
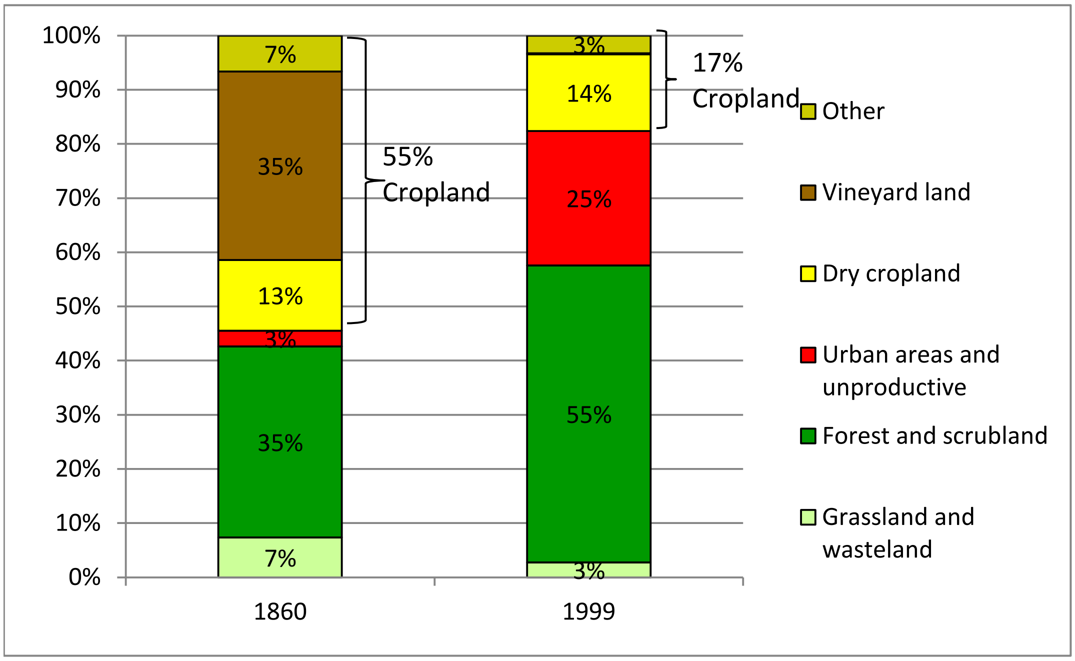


Figure 2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14%
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17%
Cropland
1860
1999
Other
Vineyard land
Dry cropland
Urban areas and unproductive
Forest and scrubland
Grassland and wasteland

Figure 3
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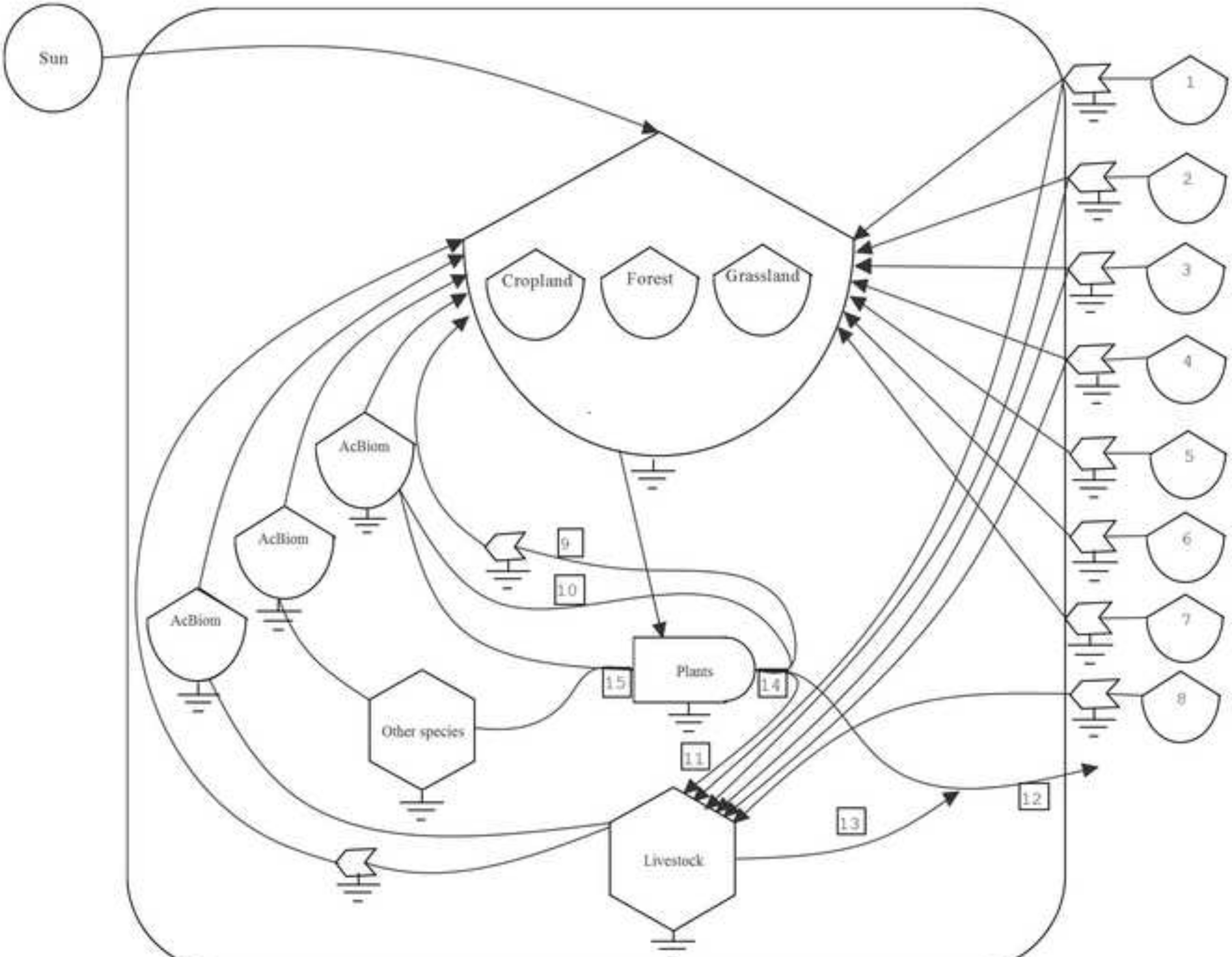
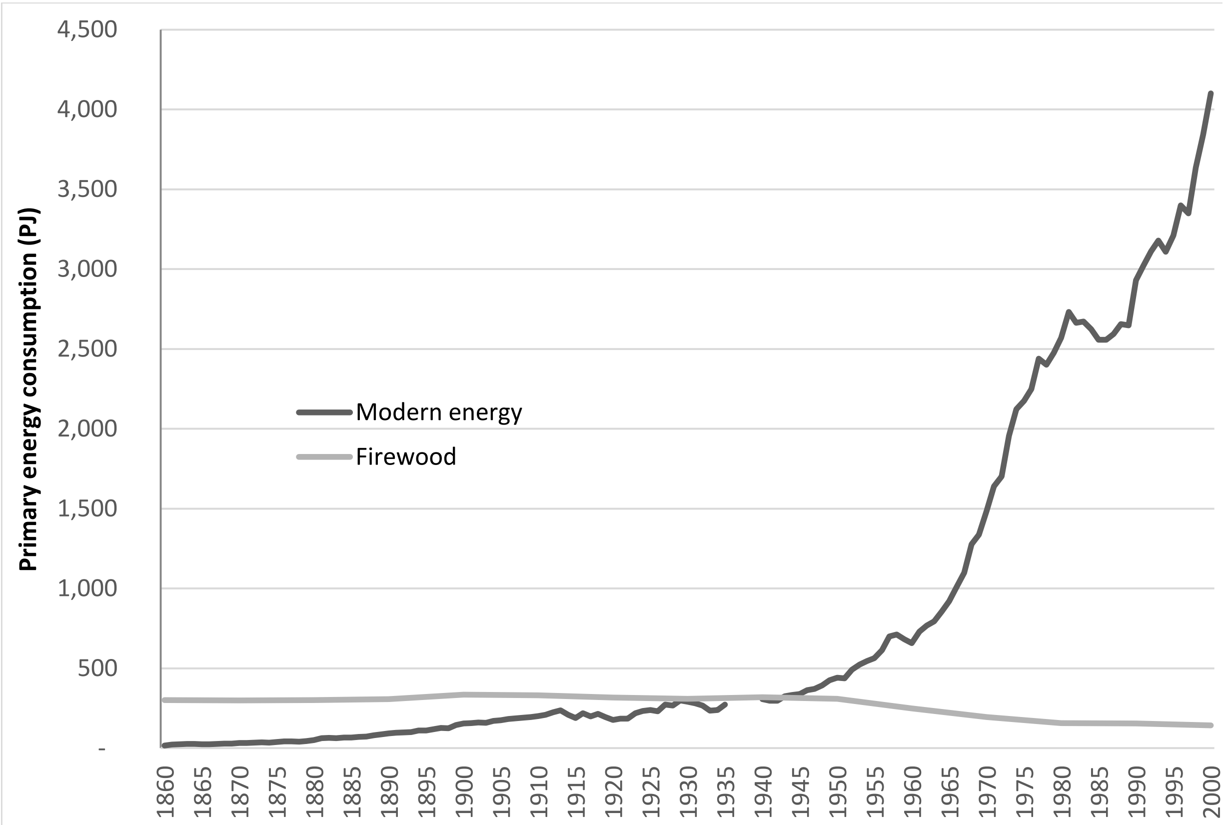


Figure 4



Primary energy consumption (PJ)
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
-
Modern energy
Firewood
1860 1865 1870 1875 1880 1885 1890 1895 1900 1905 1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995 2000

Table 1

	1860	1999
Inhabitants (number)	7,941	39,189
Population density (cap/km2)	64	327
Full-time farm workers, annual average (number)	2,057	250 *
Installed power (kilowatts)	289**	12,065
All livestock, LU 500 (number)	870	22,465
Livestock density, total area (LU 500/ha all land)	0.07	2.41
Livestock density, cropland (LU 500/ha cropland)	0.13	10.30

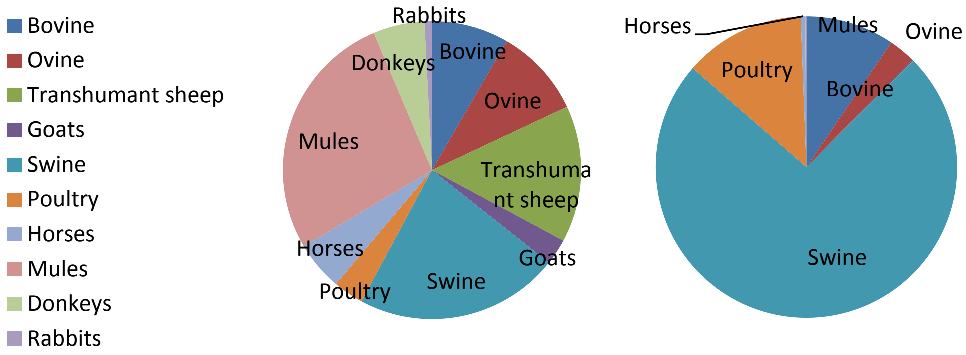


Table 2

Number in Figure3	Energy input	1860 (PJ)	1999 (PJ)
1	Human Labour	3.6	3.2
2	Humanure, human garbage and sewage	8.6	0.0
3	Embodied energy to produce machines	0.0	14.0
4	Fuel to run machines and electricity	0.0	262.9
5	Embodied energy in herbicides and pesticides	0.0	12.8
6	Embodied energy in mineral fertilizers	0.0	11.0
7	Seeds	0.0	2.0
8	Embodied energy of external feed	0.0	947.1
	Total External Inputs	12.2	1253.0

Table 3

Number in Figure3	Energy input	1860 (PJ)	1999 (PJ)
9	Biomass burnt and ploughed into cropland	47.0	0.0
10	Seeds generated within the system	3.9	2.1
10	Other buried biomass like stubble, green manure, pruning, etc.	95.7	10.3
11	Feed crops	9.7	35.8
11	Fodder crops	12.4	32.0
11	Crop by-products to animal feeding	47.9	25.5
11	Grass from grassland	13.7	1.0
11	Other animal feeding from forest and scrubland	4.4	0.0
11	Stall bedding	8.2	35.5
	Total Biomass Reused	242.9	142.2

Table 4

Number in	Energy Output or Final Produce	1860 (PJ)	1999 (PJ)	Use
12	From harvest	17.0	14.3	Food
13	Livestock barnyard produce: Meat, milk and	2.8	184.0	
12	Grape juice to make wine and olive oil	18.7	1.1	
12	Edible forest products	1.5	0.0	
12	Grapevine and olive oil pomaces sold outside	0.0	1.1	
13	Livestock barnyard produce: Slaughter by-products, wool, hides and leather	0.1	54.8	Other
12	Other industrial crops (rape, hemp)	1.5	8.5	
12	Forest timber	3.7	24.1	Fuel
12	Forest firewood	162.0		
12	Pruning and vines or trees removed to firewood	55.5	1.6	
12	Animal feed sold outside	0.0	24.0	Feed
	Final Produce	262.8	313.0	

Table 5

	Crop type	Area* (ha)	Harvest (Kg/ha)	Water content (%)	GCV (MJ/Kg)	By-products (Kg/ha)	Produce (Kg/ha)	Water content (%)	GCV (MJ/Kg)
horticultural land	**Vegetables in gardens & orchards**	83	10873	92.0	18.7	Leaves, stems, straws & weeds	11018	88	18
	Fresh fruits	42	5250	84.8	20.1	Fresh tree pruning	1170	6.5	17.1
						Tree replacement	625	30	17.1
	Nuts	42	1250	4.4	25.0	Fresh tree pruning	1170	6.5	17.1
						Tree replacement	625	30	17.1
irrigated	**Wheat**	78	1150	14.0	18.3	Straw	1805	14	17.8
						Husk	506	14	17.8
						Stubble	83	14	17.8
	Corn	55	1092	14.0	18.5	Stalks & Cobs	1670	7.9	17.1
	Hemp strains	78	1200	7.9	17.6	Hurds & shives	1356	10	17.6
	Beans	55	950	15.0	18.0	Bean straw	1377	85.5	17
rain-fed annual crops	**Wheat**	397	1135	14.0	18.3	Straw	1780	14	17.8
						Husk	499	14	17.8
						Stubble	82	14	17.8
	Associated Wheat	47	731	14.0	18.3	Straw	1147	14	17.8
						Husk	321	14	17.8
						Stubble	53	14	17.8
	Corn	96	512	14.0	18.5	Stalks & Cobs	783	7.9	17.1
	Rye & wheat mixture	509	737	14.0	18.1	Straw	1157	14	18.1
						Husk	324	14	18.1
						Stubble	53	14	18.1
	Barley	134	527	14.0	18.2	Straw	826	14	18.2
						Husk	232	14	18.2
						Stubble	38	14	18.2
	Potatoes	47	8258	66.7	18.5	Stems & Leaves	784	92	18
	Fodder	245	1743	78.0	16.8				
	Beans	151	731	15.0	18.0	Bean straw	4503	80	17
	Vetches	413	2967	80.0	20.7	Vetches straw	593	80	17
	Lupins	134	658	14.0	20.7	Lupins straw	4101	80	17
wood crops	**Olive trees**	500	185	0.0	39.7	Olive tree pruning	1884	29.2	19.6
						Olive tree browsing	539	27.9	19.6
						Tree replacement	133	29.2	19.6
						Olive oil pomace	816	40.2	22
	Vineyards	4309	1207	83.1	17.2	Vine pruning	1342	40.9	18.8
						Strain replacement	1100	40.9	18.8
						Vine leaves	1250	60.6	19
						Grapevine pomace	496	59.4	21.8

Table 6

	Crop type	Area (ha)	Harvest (Kg/ha)	Water content (%)	GCV (MJ/Kg)	By-products (Kg/ha)	Produce (Kg/ha)	Water content (%)	GCV (MJ/Kg)
horticultural land	**Vegetables**	95	24682	88.7	18.2	Leaves, stems, straws & weeds	23771	80.3	15.9
	Fresh fruits	43	5710	88.0	21.2	Fresh Tree Pruning	2414	6.2	16.9
						Tree Replacement	4133	30.0	17.1
	Nuts	47	1235	5.0	25.0	Fresh Tree Pruning	1769	5.6	17.5
						Tree Replacement	2938	30.0	17.1
irrigated	**Wheat**	0.5	5907	14.0	18.3	Straw	6492	14.0	17.8
						Husk	2599	14.0	17.8
						Stubble	427	14.0	17.8
	Barley	67	4960	14.0	18.2	Straw	4816	14.0	18.2
						Husk	2182	14.0	18.2
						Stubble	359	14.0	18.2
	Potatoes	13	23397	78.0	16.8	Stems & Leaves	3833	92.0	18.0
	Fodder	24	56726	77.5	18.5				
rain-fed annual crops	**Wheat**	123	2795	14.0	18.3	Straw	3072	14.0	17.8
						Husk	1230	14.0	17.8
						Stubble	202	14.0	17.8
	Barley	806	2296	14.0	18.2	Straw	2230	14.0	18.2
						Husk	1010	14.0	18.2
						Stubble	166	14.0	18.2
	Oat	127	1752	14.0	18.8	Straw	1596	14.0	18.0
						Husk	771	14.0	18.0
						Stubble	127	14.0	18.0
	Fodder	655	16443	74.8	18.5				
	Legumes for feed	13	798	80.0	20.7	Legume's straw	1157	85.5	17.0
	Potatoes	2	8518	78.0	16.8	Stems & Leaves	3833	92.0	18.0
	Rape and Turnip seeds	27	2700	4.9	26.7	Rape Straw	13500	5.9	19.3
wood crops	**Olive groves**	65	266	0.0	39.7	Olive tree pruning	2524	6.4	16.9
						Tree Replacement	1779	29.2	19.6
						Olive oil pomace	1192	40.2	22.0
	Vineyards	22	6355	83.5	17.2	Vine pruning	4255	8.0	17.1
						Strain Replacement	840	40.9	18.8
						Grapevine pomace	496	59.4	21.8
	Fallow	52	0	0.0	0.0				

Table 7

Produce	Area (ha)	Extraction (Kg/ha)	Water content (%)	GCV (MJ/Kg)
1860				
Timber	526	414	12	19.5
Firewood	4066	2	12	19.5
Grass (from forest and scrubland)	4066	4834	80	17.5
Acorns, mulch & others	4059	253	71	19.0
Grass (from grassland)	909	5	80	17.5
1999				
Produce	**Area (ha)**	**Extraction (Kg/ha)**	**Water content (%)**	**GCV (MJ/Kg)**
Timber and firewood	6801	206	12	19.5
Grass (from forest and scrubland)	6801	4960	80	17.5
Grass (from grassland)	340	4960	80	17.5

Table 8

	Crop type	NPPh	Herbivores		Adventitious plants		NPPact		UPH
		(GJ/ha)	(Kg/ha)	(GJ/ha)	(Kg/ha)	(GJ)	(GJ/ha)	(TJ)	(TJ)
Orchards	**Vegetables**	40.1	348	6.5	1634	29.09	75.7	6.28	2.95
	Fresh fruits	42.1	117	2.4	4000	71.20	115.7	4.82	3.06
	Nuts	56.0	175	4.4	4000	71.20	131.6	5.48	3.15
Irrigated	**Wheat**	54.7	119	2.2	296	5.28	62.2	4.86	0.58
	Corn	43.6	188	3.5	281	5.01	52.1	2.84	0.46
	Hemp	40.9	221	3.9	331	5.90	50.7	3.96	0.76
	Beans	17.9	118	2.1	1065	18.96	39.0	2.13	1.15
Rain-fed annual crops	**Wheat**	54.0	117	2.1	292	5.21	61.4	24.34	2.92
	Associated Wheat	34.8	75	1.4	188	3.36	39.5	1.87	0.22
	Corn	20.4	88	1.6	132	2.35	24.4	2.34	0.38
	Rye & wheat mixture	35.4	76	1.4	190	3.39	40.1	20.44	2.43
	Barley	25.4	54	1.0	113	2.01	28.4	3.82	0.40
	Fodder	50.9	403	7.5	3629	64.61	122.9	30.16	17.68
	Potatoes	7.6	153	2.6	134	2.39	12.5	0.59	0.24
	Beans	26.5	91	1.6	819	14.59	42.7	6.47	2.46
	Vetches	14.3	87	1.8	783	13.94	30.0	12.42	6.51
	Lupins	25.7	83	1.7	746	13.29	40.7	5.46	2.02
Wood crops	**Olive groves**	53.7	27	1.1	2248	40.01	94.8	47.39	20.54
	Vineyards	44.4	30	0.5	983	17.50	62.4	269.08	77.62

Table 9

	Crop type	NPPh	Herbivores		Adventitious plants		NPPact		UPH
		(GJ/ha)	(Kg/ha)	(GJ/ha)	(Kg/ha)	(GJ)	(GJ/ha)	(TJ)	(TJ)
Orchards	Vegetables	125.2	474	8.6	212	3.77	137.6	13.11	1.18
	Fresh fruits	102.2	64	1.4	700	12.46	116.1	5.02	0.60
	Nuts	93.7	110	2.7	700	12.46	108.9	5.10	0.71
Irrigated	Wheat	238.7	406	7.4	762	13.56	259.7	0.13	0.01
	Barley	192.8	427	7.8	511	9.11	209.7	14.01	1.13
	Potatoes	92.0	875	14.7	411	7.33	114.0	1.43	0.28
	Fodder	235.6	1189	22.0	1198	21.32	279.0	6.75	1.05
Rain-fed annual crops	Wheat	112.9	192	3.5	361	6.42	122.9	15.12	1.22
	Barley	89.2	198	3.6	237	4.22	97.1	78.18	6.29
	Oat	66.9	121	2.3	226	4.02	73.2	9.29	0.80
	Fodder	76.8	387	7.2	1198	21.32	105.2	68.95	18.66
	Legumes for feed	6.2	15	0.3	1198	21.32	27.8	0.35	0.27
	Potatoes	37.0	319	5.4	150	2.67	45.0	0.10	0.02
	Rape and Turnip seeds	314.2	128	3.4	257	4.57	322.2	8.67	0.22
Wood crops	Olive groves	90.9	25	1.0	393	7.00	98.9	6.47	0.52
	Vineyards	98.5	98	1.7	172	3.06	103.3	2.30	0.11
	Fallow	0.0	0	0.0	0	0.00	17.5	0.91	0.91

Table 10

		1860	1999
Final EROI= FP/(BR+EI)	(Eq.1)	1.03	0.22
External Final EROI= FP/EI	(Eq.2)	21.53	0.25
Edible Energy Efficiency (EEE)= Food/EI	(Eq.3)	3.28	0.16
Internal Final EROI= FP/BR	(Eq.4)	1.08	2.20
NPPact EROI= NPPact/(EI+BR)	(Eq.5)	3.13	0.56
FP/L		72.81	0.25
Food/L		11.10	65.44

Table 11

	1860			1999		
	NPP_h (GJ/ha)	UPH (GJ/ha)	NPP_{act} (GJ/ha)	NPP_h (GJ/ha)	UPH (GJ/ha)	NPP_{act} (GJ/ha)
Cropland	45.8	21.5	67.3	92.6	15.6	108.1
Grassland	15.0	2.5	17.5	2.9	14.6	17.5
Forest and scrubland	44.2	36.1	80.4	3.5	76.8	80.4
Total	42.9	25.1	68.0	24.3	60.2	84.6

Table 12

Number in Figure3		1860	1999
14=9+10+11+12-13	NPPh (PJ)	502.8	227.0
15	UPH (PJ)	294.7	561.4
14+15	NPPact (PJ)	797.4	788.4