Agroecosystem energy transitions in the old and new worlds: trajectories and determinants at the regional scale

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Abstract

Energy efficiency in biomass production is a major challenge for a future transition to sustainable food and energy provision. This study uses methodologically-consistent data on agroecosystem energy flows and different metrics of energetic efficiency from seven regional case studies in North America (USA and Canada) and Europe (Spain and Austria) to investigate energy transitions in Western agroecosystems from the late 19th to the late 20th centuries. We quantify indicators such as External Final EROI (EFEROI, i.e. final produce per unit of external energy input), Internal Final EROI (IFEROI, final produce per unit of biomass reused locally), and Final EROI (FEROI, final produce per unit of total inputs consumed). The transition is characterized by increasing final produce accompanied by increasing external energy inputs and stable local biomass reused. External inputs did not replace internal biomass reinvestments, but added to them. The results were declining EFEROI, stable or increasing IFEROI, and diverging trends in FEROI. The factors shaping agroecosystem energy profiles changed in the course of the transition: Under advanced organic agriculture of the late 19th and early 20th centuries, population density and biogeographic conditions explained both agroecosystem productivity and energy inputs. In industrialized agroecosystems, biogeographic conditions and specific socio-economic factors influenced trends toward increased agroecosystem specialization. The share of livestock products in a region's final produce was the most important factor determining energy returns on investment.

Introduction

The notion of energy transition describes the shift from traditional energy carriers (notably biomass) to modern energy sources, in particular fossil fuels (Grübler 2008). This process did not happen simultaneously around the globe or even within world regions (Gales et al. 2007). Still, consensus holds that industrialization entailed an overlapping succession of coal ("first industrial revolution") followed by crude oil and later natural gas and other modern energy sources ("second and third industrial revolutions") as major energy suppliers to socio-economic activities (Kander et al. 2014). The concept of energy transitions is particularly useful from the perspective of a biophysically-informed economic history, in which technical energy use is closely connected to economic growth (Ayres and Warr 2010).

From a socio-ecological perspective interested in the interplay of socio-economic and ecological processes, it is worthwhile to extend the analysis beyond technical energy use to all energy carriers used in a society, including biomass used as food, feed, fibers and construction materials. The concept of social metabolism (Fischer-Kowalski 1998; Gonzalez de Molina and Toledo 2014) has been used in long-term socio-ecological research (Haberl et al. 2006) to quantify changes in socio-economic material and energy use over time. This approach has demonstrated that modern energy carriers did not substitute biomass as major energy input to society, but were used in addition to increasing amounts of biomass (Krausmann 2001; Kuskova et al. 2008; Soto et al. 2016). The changing relationship between material and energy use on the one hand and land use on the other has been described as a "socio-ecological transition" (Fischer-Kowalski and Haberl 2007; Krausmann et al. 2008). However, long-term socio-ecological research has thus far largely focused on the extraction of biomass and energy from the environment, and knowledge gaps exist with regards to how much, and which type of energy was used in the process of biomass extraction.

The ratio of energy outputs to inputs, or energy return on investment (EROI), is a concept suitable to shed light on this issue. It was first developed in a study on migrating fish (Hall 1972) and later applied in the investigation of the energy efficiency of fossil energy generation (Cleveland et al. 1984; Murphy and Hall 2011; Guilford et al. 2011; Court and Fizaine 2017). In parallel, the same concept was applied to agricultural systems (Pimentel et al. 1973; Leach 1976). Currently, the literature on agricultural EROIs features three major strands:

(1) A limited, but relevant, amount of studies investigates energy returns on investment at the national scale. The energy efficiency of agricultural sectors is compared over a period of several decades up to a century (Cleveland 1995; Ozkan et al. 2004; Hamilton et al. 2013) and in some cases it covers the whole agro-food system (e.g., Steinhart and Steinhart 1974). These studies yield different results. Both energy input and agricultural production increased in most cases in the long run, resulting in more fossil fuel input per unit of final agricultural product in the course of industrialization (Pimentel et al. 1973, Smil 2000). In recent decades however, the energy return on investment increased in some countries (e.g., USA) (Hamilton et al. 2013), declined in others (e.g., Turkey) (Ozkan et al. 2004), or remained stable (e.g., Canada) (Hamilton et al. 2013).
(2) Some national-scale analyses focus on energy efficiency at the level of individual crops or agricultural products, either over time (Smil et al. 1983; Pracha and Volk 2011) or among regions (Tzilivakis et al. 2005). They provide relevant knowledge for optimizing energy inputs in crop production. Energy returns on investment are also widely used to analyze the potentials of biofuels to replace fossil fuels, generally displaying the much lower EROI of biofuels in comparison to fossil fuels (e.g., Hammerschlag 2006).
(3) A number of studies compare energy efficiency in conventional vs. organic or other alternative farming practices (Refsgaard et al. 1998; Dalgaard et al. 2001; Gomiero et al. 2008; Atlason et al. 2015), including historical practices (Cussó et al. 2006). They generally find that the higher energetic output of conventional agriculture is achieved at a lower energy return on investment. These studies usually operate at the farm or crop level, and accounting procedures differ among studies, therefore comparability and generalizability of results is limited.

These diverse approaches to energy efficiency in agricultural production offer relevant insights, but two major limitations prevail: firstly, methodological differences exist among most studies, inherent to the accounting of EROI indicators in general (Murphy et al. 2011), and agroecosystems energetics in particular (Giampietro et al. 1992). Differences owe to different research interests and resulting allocation procedures for energy inputs (Hall et al. 2011) and outputs. Therefore, the results of individual case studies remain largely context-specific. With a few important exceptions (Conforti and Giampietro 1997; Arizpe et al. 2011), systematic comparisons among energetic profiles in different cases are lacking. Secondly, studies on the energy efficiency of agricultural production focus almost exclusively on the ratio of final products to non-renewable energy inputs. While many include labor as energy input, and some include feed imports, so far local biomass inputs into agroecosystems, such as local feed or reploughed biomass, have been entirely neglected. Disregarding biomass reuse in agroecosystems impedes tracing long-term changes in agroecosystem energetics, starting in time periods when this was the major energy input to agroecosystems.

In this contribution, we close research gaps in both long-term socio-ecological research and research on agroecosystem energy analysis. We compare and discuss consistent long-term data of regional agroecosystem energy flows and energy returns on investment, including not only non-renewable but also organic energy inputs. We build on recent methodological advances to systematically account for different energy inputs in agroecosystems (Galán et al. 2016; Tello et al. 2016), which are suitable for long-term analysis. We use seven regional long-term case studies in Europe and North America to describe general features of what we call an energy transition in agroecosystems.

In the following section, we introduce the case studies, methods and data sources used. In a results and discussion section, we first describe the temporal trends in agroecosystem energy flows assessed, and then portray general features of advanced organic and industrialized agroecosystems and the factors that differentiate the case studies. We conclude by proposing future lines of research.

Case studies, methods and data

This study draws on consistent agroecosystem energy flow accounts from seven regional case studies on both sides of the Atlantic at three to five time points in the 19th and 20th centuries, many of which are presented in this Special Issue (Cunfer et al. this issue; Gingrich et al. this issue; Marco et al. this issue; Guzmán and González de Molina 2015). The case studies, despite not being exhaustive, were selected to represent relevant environments in Europe and North America: Central European lowland and prealpine agriculture (St. Florian and Grünburg, Austria), Western Mediterranean agriculture focusing on vineyards (Vallés, Catalonia, Spain) and irrigated crops (Santa Fe, Andalusia, Spain), maritime frontier agriculture (Queens, Prince Edward Island (PEI), Canada), and grasslands frontier agriculture (Kansas, USA). Many other important landscapes and cultivation practices in Europe and North America are excluded from the analysis. Figure 1a presents the location of the case studies, and Table 1 provides general biogeographic features of the case studies.

[Table 1]

The case studies vary greatly in terms of climatic conditions and agricultural structure, and display distinct trajectories over time. They also differ substantially regarding the degree of administrative integration (e.g. one county or several villages) as well as the area extent, the North American case studies exceeding the European ones by factors of up to 50. Still, each case study represents an agricultural landscape emerging from the specific local biogeographic conditions and the sum of agricultural and forestry practices of farmers operating there at a given point in time.

The European case studies in both Austria and Spain were characterized by mixed farming in the 19th century, with cropland covering more than 50% of farmland area, and livestock densities distinctly lower in Spain than in Austria (Table 2). By the end of the 20th century, European agroecosystems specialized in cropping (Santa Fe, St. Florian), pig rearing (Vallés) and grassland-based cattle rearing (Grünburg). The North American cases show distinct differences from those in the Old World. For instance, 19th century population densities and farm laborers per unit of land were much lower than in the European case studies. In Queens, PEI, cropland share and livestock density were comparable to European levels. At the time of the first data point in 1880, the two regions in Kansas had just commenced (Decatur) and finished (Nemaha) their pioneer periods, and both experienced cropland expansion during the late 19th century. By the end of the 20th century, the distribution of land-use types and livestock densities were at levels comparable to Europe, but population densities and numbers of farm workers per area remained well below the European levels.

[Table 2]

Three major energy flows through agroecosystems were accounted (Galán et al. 2016; Tello et al. 2016, Figure 1b).

(1) Final Produce comprises all biomass products from the regional agroecosystem which are used by the local community or sold to markets, including crops and wood derived from the land (land final produce) and livestock products (livestock final produce).

(2) External Inputs encompass energy embodied in labor, household wastes, non-local biomass entering the agroecosystem (market feed or seeds), and industrial energy inputs (energy embodied and used in machinery, mineral fertilizers, pesticides and electricity). External inputs are usually connected to economic costs, and, depending on their composition, may result in a variety of environmental impacts, most prominently the emission of CO_2 from fossil energy use, or the use of external land for biomass imports.

(3) Biomass Reused includes local reinvestments into the agroecosystems, such as livestock feed and litter, local seeds, and stubble burned or buried in soils (Guzmán and González de Molina 2015; Tello et al. 2016). Recycling biomass flows within the agroecosystem entails different environmental

impacts than using external inputs, and may, below a certain level, even contribute to ecosystem complexity (Marull et al. 2016). This energy flow is not considered in most studies accounting for agroecosystem energy efficiencies, and offers new insights on the transformation of agroecosystems in the course of industrialization.

[Figure 1]

The accounted flows are used to generate three interrelated energy return on investment indicators, or EROIs (Galán et al. 2016): External Final EROI (EFEROI) is the ratio of Final Produce to External Inputs (Eq. 1). EFEROI considers most of the energy inputs that are accounted in traditional agricultural energy analyses (Dalgaard et al. 2001; Schramski et al. 2013; Atlason et al. 2015), but excludes local feed inputs or manure.

Eq. 1 $$External\ Final\ EROI\ (EFEROI) = \frac{Final\ Produce}{External\ Inputs}$$

In order to investigate the important role of locally redirected energy flows, we define the Internal Final EROI (IFEROI) as the ratio of Final Produce to Biomass Reused (Eq. 2). IFEROI thus refers to the “efficiency with which intentionally recycled biomass is transformed into a product that is useful to society” (Guzmán et al. this issue).

Eq. 2 $$Internal\ Final\ EROI\ (IFEROI) = \frac{Final\ Produce}{Biomass\ Reused}$$

The third indicator, Final EROI (FEROI), is the ratio of Final Produce to Total Inputs Consumed (i.e. the sum of External Inputs and Biomass Reused) (Eq. 3).

Eq. 3 $$Final\ EROI\ (FEROI) = \frac{Final\ Produce}{Total\ Inputs\ Consumed} = \frac{Final\ Produce}{Biomass\ Reused + External\ Inputs}$$

Within the agroecosystem, we differentiate between energy entering the land system (seeds and residues inserted in soils, fuels, fertilizers, manure, pesticides, and labor for cultivation), and energy entering the livestock system (feed, litter, electricity, labor for livestock). Then, by dividing Land Final Produce and Livestock Final Produce by Land Total Inputs and Livestock Total Inputs respectively, we obtain Land EROI (Eq. 4) and Livestock EROI (Eq. 5).

Eq. 4 $$Land\ EROI = \frac{Land\ Final\ Produce}{Land\ Total\ Inputs}$$

Eq. 5 $$Livestock\ EROI = \frac{Livestock\ Final\ Produce}{Livestock\ Total\ Inputs}$$

The database used in this paper builds on case studies which have been published in recent papers (Cunfer et al. this issue; Gingrich et al. this issue; Marco et al. this issue; Guzmán and González de Molina 2015). Data on Queens, PEI, Canada, have not been published previously. A brief regional description, and a sources and methods documentation of this case study are provided in the Supplementary Information’s section 1.

For all case studies, the most relevant data sources include region-specific agricultural censuses and cadastral records, detailing land use, population and livestock numbers, yields, agricultural labor force, and agricultural machinery. National or regional information was used and downscaled to the respective regions in order to fill data gaps (e.g. on pesticides, fertilizer or electricity use). Data from census statistics were available either as archival material, as individual publications, or as databases from the respective national statistic agencies. Flows not reported in statistical records were estimated. The most important such flows are straw, which was assessed based on grain harvest and harvest indices if not reported in statistics, and grazed biomass, which was estimated based on feed supply and feed demand by local livestock, as well as information on pasture land and pasturing practices.

Energy flows were assessed by converting flows of biomass into their energy content (Guzman et al. 2014), and by calculating the embodied energy in external inputs, accounting for historical changes in industrial efficiency (Aguilera et al. 2015). For the European cases labor was accounted as the energy content of gross food intake per unit of time worked managing the agroecosystem, and embodied energy in food processing, transport and cooling was considered in the 20th century. For the North American cases labor was estimated as 2 GJ/person/year for each working age laborer (Cunfer and Krausmann 2015). For reasons of cross-case study consistency, minor differences exist between the previously-published data and the ones presented here, in particular in the Kansas case studies where per-area data refer to "farmland" here, i.e. land used for agricultural or forestry production (and to total land area in Cunfer et al. this issue), and Biomass Reused includes stubble ploughed into soils here (and excludes it in Cunfer et al. this issue).

For this comparative analysis, the agroecosystem energy flow data were analyzed with regards to potential explanatory variables, such as population density, livestock density, land use distribution, or the composition of different energy flows. Despite not being large enough for statistical analyses, the consistent data set of seven very diverse case studies enabled to develop general hypotheses on land-use intensification which go beyond the individual cases.

While complying with a consistent methodology, some caveats need to be considered given variations among the case studies. First, the choice of case studies is not representative for global trends. We thus use the sample to propose some general features of industrializing agriculture in Europe and North America, some of which may hold true also for other world regions. Secondly, due to the difference in case study areas, scale-dependent indicators need to be interpreted carefully. A smaller share of biomass reused in a smaller case study may be the result of the chosen system boundary, rather than actually lower regional energy transfers. The inverse holds true for external inputs. We compare only per-area values to level off differences in area extent, but discuss the potential bias caused by different case study sizes.

Results and discussion

Trajectories of the agroecosystem energy transition

Both Final Produce and External Inputs increased in all case studies over the time period investigated: Final Produce grew in all case studies between the first and last data points, sometimes interrupted by lower productivity in intermediate time points (Figure 2a). The smallest increase to Final Produce between the first and last data points was 24% in Queens, Canada, where forest products, which saw little productivity change, contributed over 90% of Final Produce in the 19th century and still 53% in 1995. The strongest increase in Final Produce was a multiplication by 31 in Decatur, USA, where the first data point reflects early pioneer conditions during the first years of European settlement. The combination of very low cropland extent and low wood extraction due to ecological conditions (natural grasslands) explain the low value in 1880 (Cunfer et al. this issue). At all time points, the lowest levels of Final Produce were in the Kansas case studies. In the 20th century, the highest Final Produce (around 100 GJ/ha/yr) was achieved in Santa Fe, Spain, and St. Florian, Austria, where non-edible biomass production (wood and straw) contributed significantly to Final Produce (Gingrich et al. this issue).

[Figure 2]

External Inputs of energy increased even more strongly than Final Produce in all case studies, following almost exponential trajectories (Figure 2b: almost straight lines upward along a logarithmic scale). The most pronounced increase occurred in Vallés (factor 136), while the smallest increase took place in Decatur (factor 16). After the mid-20th century, External Inputs reached levels comparable to Final Produce. Biomass Reused (Figure 2c) increased or remained stable in all the case studies in the time period investigated, with the exception of Vallés, where it declined by 26% due to the abandonment of traditional biomass intensive fertilizing techniques, and St. Florian, where livestock rearing was reduced. The flows of Biomass Reused were the most important energy input into agroecosystems throughout the time period in most case studies, and retained levels comparable to those of External Inputs at the end of the 20th century. Trends of Total Inputs Consumed in agroecosystems (Figure 2d) therefore resemble those of Biomass Reused until the mid-20th century. Only towards the end of the 20th century did Total Inputs Consumed increase due to External Inputs, while Biomass Reused remained stable. The methodology adopted here displays that the agroecosystem energy transition is characterized by a shift from largely local energy inputs (Biomass Reused dominates Total Inputs Consumed) to a combination of similar amounts of local and external energy inputs (Biomass Reused and External Inputs are similar). From a socio-ecological perspective, the increased inputs from modern energy carriers added to local agroecosystem biomass reuses, rather than replacing them.

The changes in energy inputs and outputs entailed specific trajectories of EROIs (Figure 3). EFEROI (Final Produce to External Inputs) declined in almost all case studies, quite in line with previous findings on agriculture's growing demand of external energy inputs (Pimentel et al. 1973; Smil 2000). In the 19th century, EFEROI values ranged between 7 and 12 in many case studies, i.e. Final Produce exceeded External Inputs by these factors. EFEROI was distinctly lower in Decatur and Nemaha, USA (slightly above 1), and higher in Vallés (around 22). In most case studies, the strong decline of EFEROI in the late 19th and early 20th centuries reflects increasing external energy inputs while Final Produce did not grow much.

After World War II, EFEROI converged to values between c. 2 (St. Florian) and 6 (Queens), and by 2000 declined in all case studies, to between 0.2 (Vallés) and 3.2 (Queens). EFEROI was below 1 in two case studies in 2000 (Vallés and Grünburg), indicating that farmers were investing more energy through External Inputs than they got back as Final Produce. In all other case studies, growth in Final Produce kept pace with growing External Inputs in the second half of the 20th century. Our EFEROI values for the US and Canadian case studies are similar to the ones obtained at the national scale (Steinhart and Steinhart 1974; Hamilton et al. 2013), though the empirical basis differs in scale and scope.

[Figure 3]

IFEROI, i.e. Final Produce per unit of Biomass Reused (Figure 3b), was lower than EFEROI in all case studies until the mid-20th century, given that Biomass Reused exceeded External Inputs. Towards the late 20th century, however, IFEROI increased in most case studies, because Final Produce grew strongly while Biomass Reused remained relatively stable. The only exception is Queens, Canada, where IFEROI declined in the late 20th century. The case studies in which IFEROI increased above 1 focused on intensive cropping (St. Florian), intensive pig rearing based on market feed (Vallés), or wood plantations (Santa Fe). In all other regions, IFEROI remained below 1, i.e. Biomass Reused was larger than Final Produce even in industrialized agriculture. This highlights the fact that local biomass continues to be an important energy input in industrialized agroecosystems, which has not been replaced, but merely complemented, by industrial, fossil-fuel based energy inputs.

FEROI, i.e. Final Produce per unit of Total Inputs Consumed (External Inputs plus Biomass Reused), shows no clear temporal trend across case studies (Figure 3c). With one exception (Decatur), FEROI decreased or remained stable in the period before the mid-20th century. Around this time, mechanization of agriculture already required more energy inputs, but land productivity had not increased on a large scale. This suggests farmers adopted tractors to save labor, not to increase production. In the second half of the 20th century, FEROI developed differently in the case study regions, declining slightly or strongly in some, while increasing more or less strongly in others. The most extreme cases of change after World War II were in Vallés, where specialization on import-dependent pork production caused FEROI to decline strongly, and St. Florian, where FEROI increased strongly due to specialization on high-yielding crop production and a redirection of straw from local reuse to external markets. The fact that the most extreme EROI values were reached in European case studies may be in part linked to the fact that the regions investigated in Europe were smaller than the

North American ones, and that specialization processes possibly occurring in North America are evened out through the larger area investigated.

The overall inconclusive trend of FEROI demonstrates two important features of the agroecosystem energy transition: (1) Increased productivity came as a result of more external energy inputs, while retaining some internal biomass reuses. (2) Particularly in the second half of the 20th century, regional agroecosystems changed in very diverse ways, resulting from increased regional specialization. Energy flow and EROI numbers for all case studies are provided in the Supplementary Information, section 2, and trajectories of energy input and output intensities of land use are discussed in the Supplementary Information, section 3.

Comparing European advanced organic agriculture with the North American frontier in the late 19th century

We now compare the case studies in the late 19th and early 20th centuries (i.e. 1860 in Vallés, 1864 in the St. Florian and Grünburg, and 1904 in Santa Fe) with the 1880 North American case studies. Despite the forty year time difference between the first and last data points, the European case studies reveal characteristics of advanced organic agriculture, while the North American cases are characterized by frontier conditions.

Drawing from Wrigley's notion of an "advanced organic economy" (Wrigley 1990), we define advanced organic agriculture as farming practices that 1) used very little fossil fuel, 2) relied on local resources mainly, and 3) raised land productivity through increasing labor inputs. Despite remaining in the biomass energy regime, advanced organic economies began to participate in modern, supra-regional market exchange. According to scholars like Boserup (1965, 1981) and Geertz (1963), close links existed between population density and land-use intensity under such conditions. The frontier conditions in North America were somewhat different, because already in 1880 they displayed both fossil energy input and more significant market integration. We define late 19th century North American frontier agriculture as abundant, recently colonized land with a limited agricultural labor force.

We investigate the 19th century data with the hypothesis that with increasing population density, land productivity is increased at the expense of decreasing labor productivity and decreasing IFEROIs. If so, the increased inputs of labor and Biomass Reused would outpace the resulting yield increases.

Our case studies reveal a distinction between European advanced organic agroecosystems and those in North American frontier settings. For example, the lower population density in the North American case studies (2-24 cap/km² as opposed to 64-187 cap/km² in Europe; Table 2) coincided with a lower cropland share in North America (Figure 4a). Only Grünburg stands out, where high population density at lower cropland shares resulted from regional manufacturing activities increasing population density.

[Figure 4]

The difference in cropland shares entailed different agroecosystem energy flows in European and North American agroecosystems. Final Produce per area was higher in the European case studies (21-27 GJ/ha/yr as opposed to 0.5 to 24 GJ/ha/yr in North America), and so were energy inputs per unit of area, in terms of labor and biomass reused. Only external inputs were comparable in the North American regions, despite the larger size of North American case studies. The indicator Biomass Reused proves to be a good proxy for land-use intensity in 19th century agroecosystems, as it is higher in those case studies of higher population density, higher cropland shares (Figure 4b), and higher fertilization requirements. Where cropland extent was higher, more biomass was recycled either to livestock, generating manure, or directly into soils as in Vallés. St. Florian stands out here as a region of particularly high biomass reused, caused both by high straw availability and intensive livestock management (livestock kept in stables all year required more litter than livestock grazing at least parts of the year).

While the level of different energy flows correlated with population density, energy returns on investment show no clear interrelation with population density. Instead, energy returns on investment had to do with the land uses other than cropland. High forest shares were related to higher EFEROI values, and high pasture shares to low EFEROI values (Figures 4c and 4d). The land-use types other than cropland were greatly influenced by biogeographical factors such as climate and native vegetation. Extensive land use requiring little labor per unit area (that is, land use of low "input-intensity", (Erb et al. 2013)), allowed for wood extraction in Queens, and for rangeland livestock rearing in Kansas. Forests yield high energetic output at low input, while livestock rearing yields low Final Produce per unit of labor input. Therefore, in our accounting metrics, the lower energetic efficiency of regions with low forest shares (in our case studies: particularly in Kansas) was the result of low rainfall favoring specific management practices.

At a higher level of abstraction, the data allows for a thought experiment discerning two different types of land-use intensification. In traditional European agriculture, where croplands were already covering high shares of suitable land, increases to agricultural production could only be achieved by intensification, which required more inputs of labor and Biomass Reused when no substantial external inputs were available, and resulted in stable or declining EROIs. This supports our initial hypothesis. In a frontier situation such as the one in Kansas however, we see a different trajectory: cropland expansion at the expense of extensive livestock rearing may have yielded higher Final Produce at declining inputs of labor and Biomass Reused per unit of output, thus resulting in increasing energy returns on investment.

Industrialized agroecosystems: high input, high output and regional specialization

By the late 20th century, some of the biophysical constraints to organic agriculture had lost their relevance. External energy sources had become available in substantial amounts, adding to local biomass flows. Due to low energy prices, energy turned from a biophysical constraint into just one of many economic factors influencing farmers' farm management decisions. Our data suggest that agroecosystem energy efficiency in the late 20th century depended greatly on the particular specialization path followed by agricultural production in each region.

The amount of Final Produce generated by industrialized agroecosystems was strongly related to cropland productivity in our case studies. Places where cropland Final Produce per cropland area was highest (St. Florian and Santa Fe) also exhibited the highest total Final Produce per total land area. Likewise, the regions with lowest cropland productivity displayed lowest overall land productivity (Figure 5a). This reflects the fact that croplands contributed more than 80% to Final Produce in some case studies (St. Florian and the Kansas case studies), while livestock production or forestry compensated for the difference in the others. Cropland intensification took place particularly in those regions with favorable biogeographic conditions (or, as in Santa Fe, with conditions suitable for irrigation). Figure 5b illustrates that cropland productivity in 2000 correlated strongly with cropland productivity in the late 19th century. In most case studies, cropland productivity increased by a factor 2 to 3 between the late 19th century and the end of the 20th century.

[Figure 5]

The level of energy inputs into each agroecosystem was related to a number of variables. In case studies with low livestock densities and intensive cropping (Santa Fe, Spain, and Decatur and Nemaha, USA), fuels for tractors and fertilizers dominated energy inputs. In the other case studies, external feed inputs for livestock were the most important energy inputs. Regions where livestock density was highest and livestock products contributed 20% or more to Final Produce (Grünburg and Vallés) featured the highest Total Inputs Consumed (130 and 153 GJ/ha/yr, respectively). Still, the two livestock regions display significant differences. In Grünburg, where steep topography obstructed industrialized cropping, grassland-based cattle rearing dominated. Important shares of feed were provided locally, and manure was returned to the land. Industrialized pig and poultry production in Vallés occurred more independently from local biogeographic conditions, and was favored for socio-economic reasons. In the feedlots of Vallés, Biomass Reused played only a minor role, and external feed inputs exceeded livestock Biomass Reused by a factor 7 in 1999. The two cases demonstrate structural differences in energetic profiles depending on the type of livestock management, which have been displayed to be considerable e.g. at the national scale in the United States (Pelletier et al. 2011).

While the levels of Final Produce were linked to cropland productivity, livestock played a bigger role in shaping energy inputs. Land-based biomass production (both on agricultural land and forests) and livestock production differ not only in terms of energy outputs and inputs, but also in the ratio between the two, i.e. their energetic conversion efficiency. Figure 5c presents the indicators "Land EROI" and "Livestock EROI" in all our case studies in 2000. The comparison shows that energy conversion efficiency in land-based biomass production exceeded energy efficiency in livestock production by around a factor 10. The differences between the case studies can be attributed in part to differences in the composition of land use and livestock species. Livestock EROI was lowest in Decatur, USA, where cattle, the least energy efficient major livestock species in our case studies, accounted for over 95% of standardized livestock units. In Vallés, where livestock rearing was dominated by pork production, and ruminants account for less than 10% of total livestock, livestock EROI was highest. Similarly, land-use composition explains part of the differences in land EROIs, with the highest value in St. Florian, where 77% of farmland was used as cropland, the most productive land-use type in industrialized agroecosystems, and the lowest in Vallés (18% cropland).

The share of livestock products in Final Produce was an important factor shaping differences in FEROI (the ratio between Final Produce and Total Inputs Consumed), as shown in Figure 5d. With the high energy input requirements of livestock production and the relatively inefficient conversion to Final Produce, the relevance of livestock products significantly affected FEROI values. The potential for high energetic dependence on External Inputs, and for providing remote markets (rather than local subsistence), allowed for strong and diverging specialization in industrialized agroecosystems. An agroecosystem like the one in Vallés, where feed demand greatly exceeded local feed production, would not have been possible under advanced organic conditions. Our data suggest that fossil-fuel based energy inputs loosened the links between population density and land-use intensity. Instead, a combination of biogeographic conditions and socio-economic factors led to specialization of agroecosystems on particular production types, determining the energetic profiles of regional agroecosystems.

Conclusions and outlook

In the course of industrialization, biomass production was increased at the expense of increasing amounts of modern energy inputs. Our analysis, based on the consistent comparison of seven regional case studies across the Atlantic, confirms this general observation and adds two major insights on what we call an agroecosystem energy transition. (1) Energetic transfers within agroecosystems (e.g., local feed and litter provision), which accounted for the largest fraction of agroecosystem energy inputs in advanced organic and frontier agriculture, remained a significant energy input throughout the period. This means that, despite growing external energy inputs, both industrial and biotic, overall energy efficiency of agroecosystems did not decline as much as suggested by previous work. (2) The factors explaining differences among agroecosystem energy efficiencies changed in the course of industrialization: in pre-industrial and frontier agroecosystems these factors were mostly biophysical (population density, suitability for wood extraction versus grazing). In industrialized agroecosystems however, regional specialization on specific agricultural production processes, partly favored by biogeographic conditions but partly by socio-economic factors, determined energetic profiles of regional agroecosystems.

Based on our findings, we identify two important lines of future research.

(1) The results here are based on a sample of agroecosystems representative of specific agroecological and geographical zones with a specific land-use history. Future research investigating other regions with different agricultural practices and different land-use histories, and more samples e.g. including Asian or African case studies, and plantation, rice cultivation or rangeland systems, are required to shed light on agroecosystem energy trajectories under different agroecological and socio-cultural conditions. In addition, work at different scales, ranging from the farm household to the village, the province, country or world region, will allow for identifying the effects of scale-specific trajectories, such as regional specialization.

(2) Exploring the links of agroecosystem energy transitions to both socio-economic and ecological processes promises to yield important insights. At the regional scale, landscape metrics, soil nutrient balances, greenhouse gas emission balances, or the Human Appropriation of Net Primary Production may help explain different types of ecological pressures exerted by different energy profiles. Agroecological EROI indicators (Guzmán et al. this issue; Guzmán and González de Molina 2015) provide insights about energy flows related to the state of fund elements of agroecosystems and thus reveal details of their ecological sustainability. Incorporating a socio-economic perspective on the other hand, e.g. by investigating prices of agricultural products or production factors, or analyzing the role of political decision-making related to land-use change, informs about the complex rationale of farmers' decision-making in particular during agricultural specialization of the 20th century. Ultimately, such research could offer insights on sustainable land-use intensification by identifying energy-efficient agroecological optimization strategies which meet social needs while sustaining agroecological functioning.

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References

Aguilera E, Guzmán G, Infante-Amate J, Soto D, Garcia-Ruiz R, Herrera A, Villa I, Torremocha E, Carranza G, Gonzalez de Molina M (2015) Embodied energy in agricultural inputs. Incorporating a historical perspective. Documentos de Trabajo 1507, Sociedad Española de Historia Agraria (SEHA)

Arizpe N, Giampietro M, Ramos-Martin J (2011) Food Security and Fossil Energy Dependence: An International Comparison of the Use of Fossil Energy in Agriculture (1991-2003). Crit Rev Plant Sci 30:45–63. doi: 10.1080/07352689.2011.554352

Atlason RS, Kjaerheim KM, Davidsdottir B, Ragnarsdottir KV (2015) A Comparative Analysis of the Energy Return on Investment of Organic and Conventional Icelandic Dairy Farms. Icel Agric Sci 28:29–42. doi: 10.16886/IAS.2015.04

Ayres RU, Warr B (2010) The economic growth engine: how energy and work drive material prosperity. Edward Elgar Publishing, Cheltenham, Northampton

Boserup E (1965) The conditions of agricultural growth. Aldine Chicago

Boserup E (1981) Population and Technological Change - A study of Long-Term Trends. The University of Chicago Press, Chicago

Cleveland C (1995) The direct and indirect use of fossil fuels and electricity in USA agriculture, 1910–1990. Agric Ecosyst Environ 55:111–121. doi: 10.1016/0167-8809(95)00615-Y

Cleveland CJ, Costanza R, Hall CAS, Kaufmann R (1984) Energy and the U.S. Economy: A Biophysical Perspective. Science 225:890–897. doi: 10.1126/science.225.4665.890

Conforti P, Giampietro M (1997) Fossil energy use in agriculture: an international comparison. Agric Ecosyst Environ 65:231–243. https://doi.org/10.1016/S0167-8809(97)00048-0

Court V, Fizaine F (2017) Long-Term Estimates of the Energy-Return-on-Investment (EROI) of Coal, Oil, and Gas Global Productions. Ecol Econ 138:145–159. doi: 10.1016/j.ecolecon.2017.03.015

Cunfer G, Krausmann F (2015) Adaptation on an Agricultural Frontier: Socio-Ecological Profiles of Great Plains Settlement, 1870–1940. J Interdiscip Hist 46:355–392. doi: 10.1162/JINH_a_00868

Cunfer G, Watson A, Joshua MacFadyen (this issue) Energy profiles of an agricultural frontier: the American Great Plains, 1860–2000. Reg Environ Change online first. doi: 10.1007/s10113-017-1157-x

Cussó X, Garrabou R, Tello E (2006) Social metabolism in an agrarian region of Catalonia (Spain) in 1860 to 1870: Flows, energy balance and land use. Ecol Econ 58:49–65. doi:10.1016/j.ecolecon.2005.05.026

Dalgaard T, Halberg N, Porter JR (2001) A model for fossil energy use in Danish agriculture used to compare organic and conventional farming. Agric Ecosyst Environ 87:51–65. doi: 10.1016/S0167-8809(00)00297-8

Erb K-H, Haberl H, Jepsen MR, Kuemmerle T, Lindner M, Müller D, Verburg P, Reenberg A (2013) A conceptual framework for analysing and measuring land-use intensity. Curr Opin Environ Sustain 5:464–470. doi: 10.1016/j.cosust.2013.07.010

Fischer-Kowalski M (1998) Society’s Metabolism. The Intellectual History of Material Flow Analysis, Part I: 1860-1970. J Ind Ecol 2:61–78.

Fischer-Kowalski M, Haberl H (2007) Socioecological transitions and global change: Trajectories of social metabolism and land use. Edward Elgar Publishing

Galán ES, Padró R, Marco I, Tello E, Cunfer G, Guzman GI, Gonzalez de Molina M, Krausmann F, Gingrich S, Sacristan V, Moreno D (2016) 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). Ecol Model 336:13–25. doi: 10.1016/j.ecolmodel.2016.05.012

Gales B, Kander A, Malanima P, de Rubio M (2007) North versus South: Energy transition and energy intensity in Europe over 200 years. Eur Rev Econ Hist 11:219–253.

Geertz C (1963) Agricultural involution: the process of ecological change in Indonesia. Univ of California Press, Berkeley and Los Angeles

Giampietro M, Cerretelli G, Pimentel D (1992) Energy analysis of agricultural ecosystem management: human return and sustainability. Agric Ecosyst Environ 38:219–244. doi: 10.1016/0167-8809(92)90146-3

Gingrich S, Theurl MC, Erb K, Krausmann F (this issue) Regional specialization and market integration: Agroecosystem energy transitions in Upper Austria. Reg Environ Change online first. doi: doi:10.1007/s10113-017-1145-1

Gomiero T, Paoletti MG, Pimentel D (2008) Energy and Environmental Issues in Organic and Conventional Agriculture. Crit Rev Plant Sci 27:239–254. doi: 10.1080/07352680802225456

Gonzalez de Molina M, Toledo VM (2014) The Social Metabolism. A Socio-Ecological Theory of Historical Change. Springer, New York

Grübler A (2008) Energy transitions. In: Cleveland CJ (ed) Encyclopedia of Earth. Online: http://www.eoearth.org/article/Energy_transitions

Guilford MC, Hall CAS, O’Connor P, Cleveland CJ (2011) A New Long Term Assessment of Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production. Sustainability 3:1866–1887. doi: 10.3390/su3101866

Guzman G, Aguilera E, Soto D, lnfante-Amate J, Garcia-Ruiz R, Herrera A, Villa I, Gonzalez de Molina M (2014) Methodology and conversion factors to estimate the net primary productivity of historical and contemporary agroecosystems. Documentos de Trabajo 1407, Sociedad Española de Historia Agraria (SEHA)

Guzmán Casado GI, González de Molina M (2009) Preindustrial agriculture versus organic agriculture. Land Use Policy 26:502–510. doi: 10.1016/j.landusepol.2008.07.004

Guzmán GI, González de Molina M (2015) Energy Efficiency in Agrarian Systems From an Agroecological Perspective. Agroecol Sustain Food Syst 39:924–952. doi: 10.1080/21683565.2015.1053587

Guzmán GI, González de Molina M, Soto Fernandez D, Infante-Amate J, Aguilera E (this issue) Spanish agriculture from 1900 to 2008: a long-term perspective on agroecosystem energy from an agroecological approach. Reg Environ Change. doi: 10.1007/s10113-017-1136-2

Haberl H, Winiwarter V, Andersson K, Ayres RU, Boone C, Castillo A, Cunfer G, Fischer-Kowalski M, Freudenburg WR, Furman E, Kaufmann R, Krausmann F, Langthaler E, Lotze-Campen H, Mirtl M, Redman CL, Reenberg A, Wardell A, Warr B, Zechmeister H (2006) From LTER to LTSER: conceptualizing the socioeconomic dimension of long-term socioecological research. Ecology & Society 11(2):13 [online]. http://www.ecologyandsociety.org/vol11/iss2/art13/

Hall CAS (1972) Migration and Metabolism in a Temperate Stream Ecosystem. Ecology 53:585–604. doi: 10.2307/1934773

Hall CAS, Dale BE, Pimentel D (2011) Seeking to Understand the Reasons for Different Energy Return on Investment (EROI) Estimates for Biofuels. Sustainability 3:2413–2432. doi: 10.3390/su3122413

Hamilton A, Balogh S, Maxwell A, Hall C (2013) Efficiency of Edible Agriculture in Canada and the U.S. Over the Past Three and Four Decades. Energies 6:1764–1793. doi: 10.3390/en6031764

Hammerschlag R (2006) Ethanol’s Energy Return on Investment: A Survey of the Literature 1990−Present. Environ Sci Technol 40:1744–1750. doi: 10.1021/es052024h

Kander A, Malanima P, Warde P (2014) Power to the people: energy in Europe over the last five centuries. Princeton University Press, Princeton

Krausmann F (2001) Land use and industrial modernization: an empirical analysis of human influence on the functioning of ecosystems in Austria 1830–1995. Land Use Policy 18:17–26. doi: doi:10.1016/S0264-8377(00)00042-9

Krausmann F, Schandl H, Sieferle RP (2008) Socio-ecological regime transitions in Austria and the United Kingdom. Ecol Econ 65:187–201. doi: 10.1016/j.ecolecon.2007.06.009

Kuskova P, Gingrich S, Krausmann F (2008) Long term changes in social metabolism and land use in Czechoslovakia, 1830–2000: An energy transition under changing political regimes. Ecol Econ 68:394–407. doi: 10.1016/j.ecolecon.2008.04.006

Leach G (1976) Energy and food production. IPC Science and Technology Press, Guildford

Lieth H (1975) Modeling the primary productivity of the world. In: Lieth H, Whittaker RH (eds) Primary productivity of the biosphere. Springer, New York, pp 237–263

MacFadyen J (2016) The Fertile Crescent: Agricultural Land Use on Prince Edward Island, 1861-1971. In: MacDonald E, MacFadyen J, Novaczek I (eds) Time and a Place: An Environmental History of Prince Edward Island. McGill-Queen’s University Press, Montreal, pp 161-194

Marco I, Padró R, Cattaneo C, Caravaca J, Tello E (this issue) From vineyards to feedlots: a fund-flow scanning of sociometabolic transition in the Vallès County (Catalonia) 1860-1956-1999. Reg Environ Change. doi: 10.1007/s10113-017-1172-y

Marull J, Font C, Padró R, Tello E Panazzolo A (2016) Energy–Landscape Integrated Analysis: A proposal for measuring complexity in internal agroecosystem processes (Barcelona Metropolitan Region, 1860–2000). Ecol Indic 66:30–46. doi: 10.1016/j.ecolind.2016.01.015

Murphy DJ, Hall CAS (2011) Energy return on investment, peak oil, and the end of economic growth: EROI, peak oil, and the end of economic growth. Ann N Y Acad Sci 1219:52–72. doi: 10.1111/j.1749-6632.2010.05940.x

Murphy DJ, Hall CAS, Dale M, Cleveland C (2011) Order from Chaos: A Preliminary Protocol for Determining the EROI of Fuels. Sustainability 3:1888–1907. doi: 10.3390/su3101888

Ozkan B, Akcaoz H, Fert C (2004) Energy input–output analysis in Turkish agriculture. Renew Energy 29:39–51. doi: 10.1016/S0960-1481(03)00135-6

Pelletier N, Audsley E, Brodt S, Garnett T, Henriksson P, Kendall A, Kramer K, Murphy D, Nemecek T, Troell M (2011) Energy intensity of agriculture and food systems. Annu Rev Environ Resour 36:223–246. doi: 10.1146/annurev-environ-081710-161014

Pimentel D, Hurd LE, Bellotti AC, Forster M, Oka I, Sholes O, Whitman R (1973) Food Production and the Energy Crisis. Science 182:443–449. doi: 10.1126/science.182.4111.443

Pracha AS, Volk TA (2011) An Edible Energy Return on Investment (EEROI) Analysis of Wheat and Rice in Pakistan. Sustainability 3:2358–2391. doi: 10.3390/su3122358

Refsgaard K, Halberg N, Kristensen ES (1998) Energy utilization in crop and dairy production in organic and conventional livestock production systems. Agric Syst 57:599–630. doi: 10.1016/S0308-521X(98)00004-3

Schramski JR, Jacobsen KL, Smith TW, Williams M, Thompson T (2013) Energy as a potential systems-level indicator of sustainability in organic agriculture: Case study model of a diversified, organic vegetable production system. Ecol Model 267:102–114. doi: 10.1016/j.ecolmodel.2013.07.022

Smil V (2000) Feeding the World. A Challenge for the Twenty-First Century. MIT Press, Cambridge

Smil V, Nachman P, Long TV (1983) Energy analysis and agriculture: an application to US corn production. Westview, Boulder, CO

Soto D, Infante-Amate J, Guzmán GI, Cid A, Aguilera A, Garcia-Ruiz R, Gonzalez de Molina M (2016) The social metabolism of biomass in Spain, 1900–2008: From food to feed-oriented changes in the agro-ecosystems. Ecol Econ 128:130–138. doi: 10.1016/j.ecolecon.2016.04.017

Steinhart SS, Steinhart CE (1974) Energy use in the US food system. Science 184:307–316.

Tello E, Galán E, Sacristán V, Cunfer G, Guzmán I, González de Molina M, Krausmann F, Gingrich S, Padró R, Marco I, Moreno-Delgado D (2016) Opening the black box of energy throughputs in farm systems: A decomposition analysis between the energy returns to external inputs, internal biomass reuses and total inputs consumed (the Vallès County, Catalonia, c.1860 and 1999). Ecol Econ 121:160–174. doi: 10.1016/j.ecolecon.2015.11.012

Tzilivakis J, Warner DJ, May M, Lewis KA, Jaggard K (2005) An assessment of the energy inputs and greenhouse gas emissions in sugar beet (Beta vulgaris) production in the UK. Agric Syst 85:101–119. doi: 10.1016/j.agsy.2004.07.015

Wrigley EA (1990) Continuity, chance and change: The character of the industrial revolution in England. Cambridge University Press

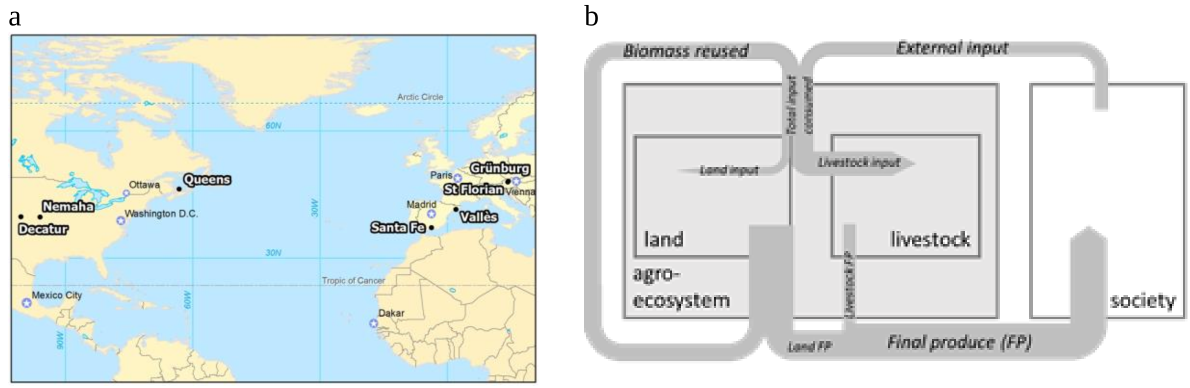

Figure 1 (a) location of case studies and (b) conceptual framework of energy flows accounted

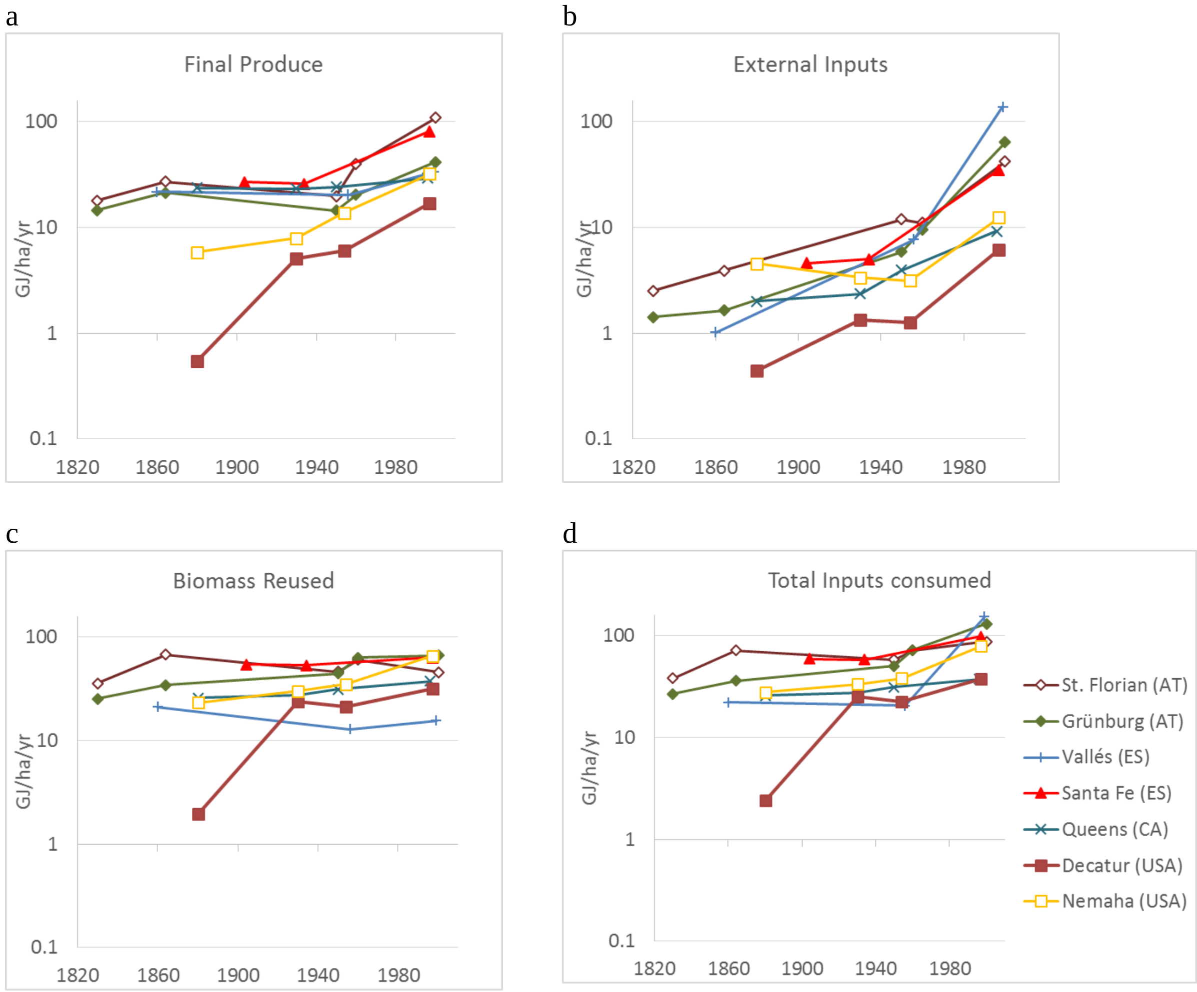

Figure 2 Agroecosystem energy outputs (a. Final Produce) and inputs (b. External Inputs, c. Biomass Reused, and d. Total Inputs Consumed, i.e. the sum of External Inputs and Biomass Reused); log scale

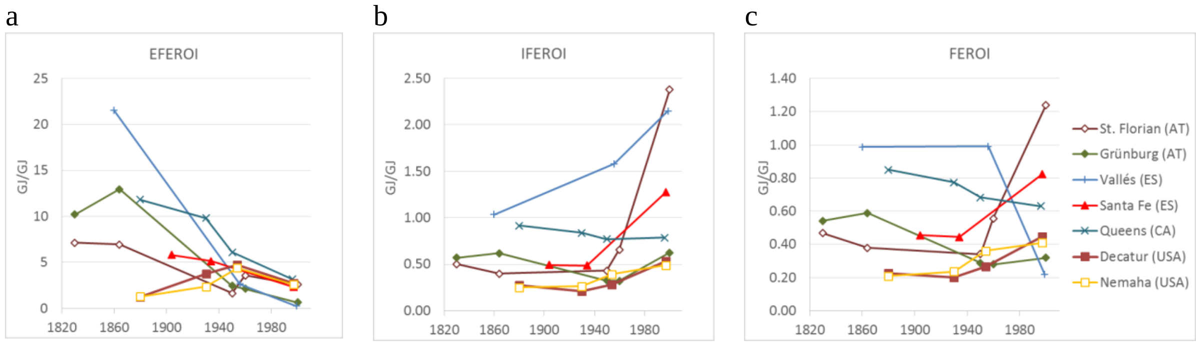

Figure 3 Energy returns on Investment (EROIs): a. External Final EROI (EFEROI, ratio of Final Produce to External Inputs); b. Internal Final EROI (IFEROI, ratio of Final Produce to Biomass Reused); c. Final EROI (FEROI, ratio of Final Produce to Total Inputs Consumed (i.e. the sum of External Inputs plus Biomass Reused)

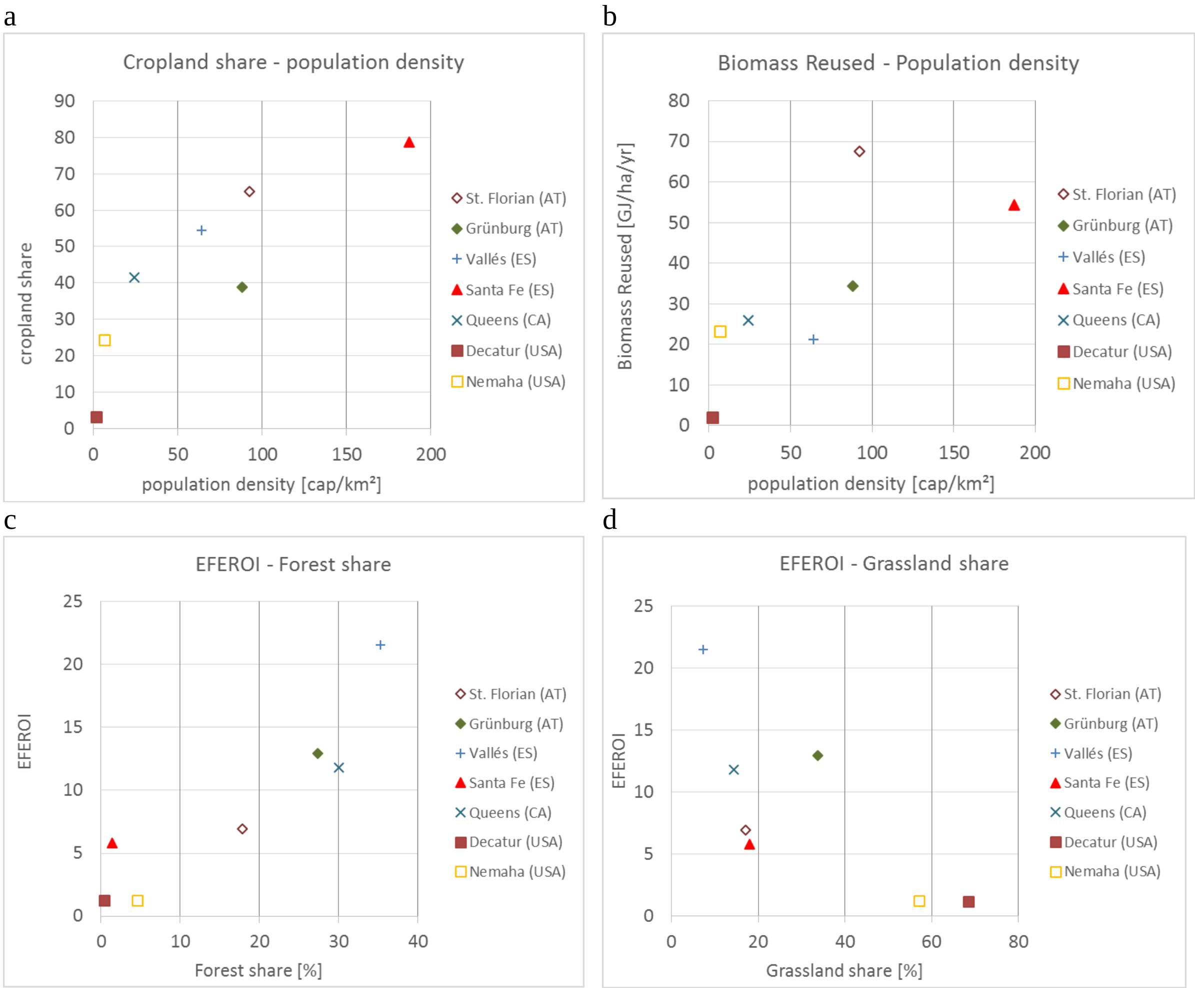

Figure 4 Features of advanced organic agroecosystems: the share of cropland in farmland area (a) and the amount of Biomass Reused (b) correlated positively with population density. However, energy efficiency (EFEROI) was more determined by other land-use types, i.e. forest share (c) and grassland share (d)

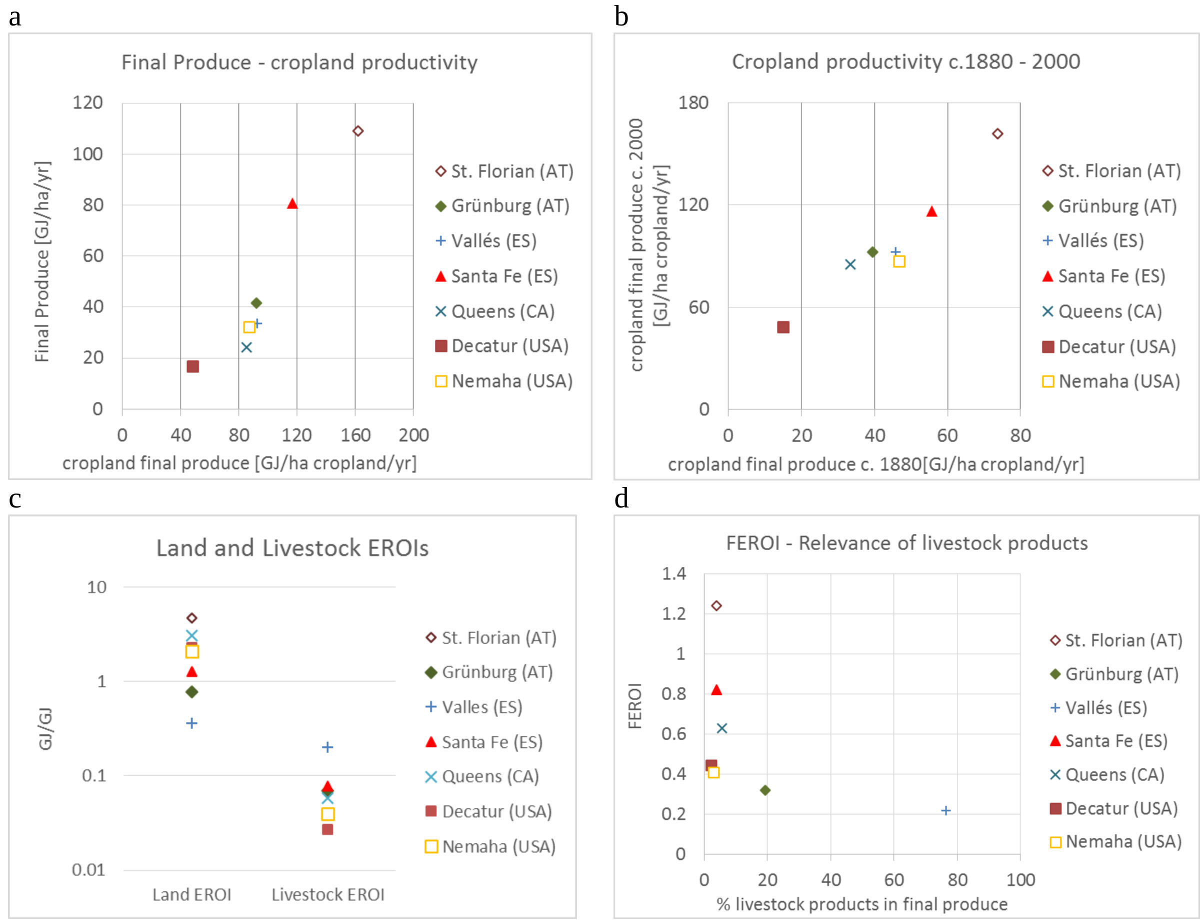

Figure 5 features of industrialized agroecosystems: (a) cropland productivity explains much of the final productivity and is (b) strongly linked to cropland productivity in advanced organic/frontier agriculture of the respective case study. (c) Energy efficiency differs greatly between land-based and livestock-based biomass production, log scale; (d) relevance of livestock products explains much of Final EROI (FEROI).

Table 1: Biogeographic features of the case study regions. Climate data are derived from the respective nearest weather station and refer to current time periods: HISTALP database (St. Florian and Grünburg), Atles Climàtic de Catalunya (Valles), Climatedata.eu (Santa Fe), Usclimatedata.com (Decatur and Nemaha) and climate.weather.gc.ca (Queens). Potential NPP was roughly assessed based on climate data according to Lieth (1975).

	Case study region	Province and country	Rainfall [mm/yr]	Mean Temp. [°C]	Potential NPP [gDM/ m²/yr]	Time period	# time points	Previous work on the region
Europe	St. Florian	Upper Austria, Austria	860	9.5	1,276	1830-2000	5	Gingrich et al. this issue
	Grünburg	Upper Austria, Austria	1000	8.9	1,309	1830-2000	5	Gingrich et al. this issue
	Vallès	Catalonia, Spain	700	13.9	1,089	1860-1999	3	Galán et al. 2016; Tello et al. 2016; Marco et al. this issue
	Santa Fe	Andalusia, Spain	358	14.7	618	1904-1997	3	Guzman and Gonzalez de Molina 2009; Guzmán and González de Molina 2015
North America	Queens	Prince Edward Island, Canada	1,158	5.7	1,038	1880-1995	4	MacFadyen 2016; Supplementary Information section 1
	Nemaha	Kansas, USA	860	11.4	1,276	1880-1997	4	Cunfer et al. this issue
	Decatur	Kansas, USA	525	10.7	861	1880-1997	4	Cunfer et al. this issue

Table 2: Agroecosystem features of the case study regions. Farmland area includes all land potentially used in agriculture or forestry, i.e. all land excluding unproductive and settlement areas. Data based on own calculations, see text.

Case Studies		**Year**	**Population density**	Farmers per km² Farmland	Farmland	Cropland	Woodland	Grassland	Livestock density
			cap/km2	cap/km²	ha	% farmland	% farmland	% farmland	LSU500/km² farmland
Europe	St. Florian, AT	1864	92.4	40	5,008	65.1	17.9	17.1	54.5
		1950	172.5	23	8,000	57.0	18.2	24.8	50.6
		2000	389.2	10	6,733	76.6	18.1	5.2	32.4
	Grünburg, AT	1864	88.0	27	5,924	38.9	27.4	33.7	39.8
		1950	78.0	22	10,065	30.7	22.4	46.8	49.1
		2000	84.5	15	8,700	31.6	30.5	37.8	98.6
	Vallés, ES	1860	64.1	17	12,037	56.1	36.4	7.5	7.2
		1956	100.8	10	11,680	36.5	42.7	20.7	9.0
		1999	326.7	3	9,323	23.4	72.9	3.7	241.1
	Santa Fe, ES	1904	187.3	44	3,782	80.3	1.4	18.3	22.0
		1934	242.1	59	3,601	84.1	6.2	9.7	38.0
		1997	320.9	17	3,569	81.8	12.3	5.9	37.8
North America	Queens, CA	1880	24.3	11	170,193	48.4	35.0	16.6	26.3
		1950	21.6	6	166,811	41.5	37.0	21.5	30.3
		1995	36.5	0.8	164,527	43.4	47.9	8.8	37.3
	Nemaha, USA	1880	6.6	3	161,415	28.3	5.3	66.5	27.3
		1954	7.8	3	175,184	62.3	5.1	32.6	33.3
		1997	5.8	1	176,522	56.8	4.9	38.3	36.9
	Decatur, USA	1880	1.9	1	162,179	4.3	0.6	95.2	2.3
		1954	2.7	0.8	223,599	58.3	0.7	41.0	12.6
		1997	1.5	0.2	222,170	53.0	0.9	46.1	22.1