Science of the Total Environment 645 (2018) 119–129

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

At the core of the socio-ecological transition: Agroecosystem energy fluxes in Austria 1830–2010

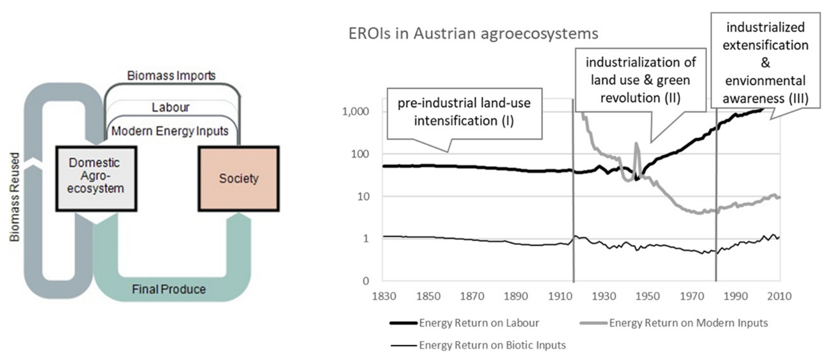
Simone Gingrich *, Fridolin Krausmann

Institute of Social Ecology, Department of Economics and Social Sciences, University of Natural Resources and Life Sciences, Vienna, Austria

HIGHLIGHTS

- We studied Austrian Agroecosystem Energy Returns on Investment for 1830–2010.
- Three distinct periods of land-use intensification are identified.
- Pre-industrial intensification: no modern energy inputs, EROIs slightly declined
- Industrialization: boosting modern inputs, EROIs declined except returns on labor
- Industrial extensification: less livestock, more wood, EROIs recovered

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 March 2018
Received in revised form 7 June 2018
Accepted 6 July 2018
Available online 17 July 2018

Editor: R Ludwig

Keywords:
Agroecosystem
Energy return on investment
Energy efficiency
Socio-ecological transition

ABSTRACT

Analyses of energy efficiency in biomass production offer important insights in the context of sustainable land management and biomass production. However, much of the previous research on the topic has focused on the energy efficiency of either food or energy provision. Only recently, comprehensive analyses at the total agroecosystem level have been operationalized, studying long-term change in agroecosystem energetics in the course of the socio-ecological transition. We contribute to this line of research by offering an empirical assessment of agroecosystem energetics for the case of Austria, covering the period 1830–2010 at an annual resolution. We present a quantitative assessment of energy inputs, outputs and internal energy fluxes of Austria's agroecosystem, including crop production, livestock production and forestry, as well as energy return on investment indicators. We identify three major periods: (1) "pre-industrial land-use intensification" (1830–1914) is characterized by moderate agricultural growth based on increased biomass recirculation, declining wood harvest, and, probably, slightly declining energy returns on investments. (2) From 1918 to 1985, "industrialization of land use and the green revolution" exhibits a substitution of labor by modern energy inputs, while livestock continued to rely greatly on domestic biomass. (3) "Industrialized extensification and environmental awareness" (1986–2010) features increasing energy efficiency due to declines in livestock numbers, a shift towards forestry, and a rising amount of final products from croplands at stable energy inputs. We discuss these periods in the context of changes in both ecological impacts and social metabolism, and identify trade-offs among food and bioenergy provision.

* Corresponding author at: Schottenfeldgasse 29, 1070 Vienna, Austria.
E-mail address: simone.gingrich@boku.ac.at (S. Gingrich).

https://doi.org/10.1016/j.scitotenv.2018.07.074

1. Introduction

Biomass is an indispensable resource, both as food sustaining the endosomatic metabolism of humans, and as fuel and fiber supporting the exosomatic social metabolism (Gonzalez de Molina and Toledo, 2014; Steinberger et al., 2010). Despite persisting problems of undernourishment in some world regions, global biomass production has by and large kept pace with population growth throughout the past century (Krausmann et al., 2013) and enabled improvements in diets in many parts of the world (Kastner et al., 2012; Koning et al., 2008). The relevance of biomass as energy carrier on the other hand has declined globally since around 1950, due to increasing fossil fuel use (Fernandes et al., 2007). Future sustainable provision of biomass will face the challenge of meeting societal needs while complying with ecological constraints (Raworth, 2012). In this context, energy efficiency of biomass production plays a crucial role: Changes in energy supply are expected in the future both due to fossil fuel depletion (Mohr et al., 2015; Shafiee and Topal, 2009), and due to increasing biofuel demand for climate change mitigation purposes (IPCC, 2014). These changes pose double burdens on biomass production: not only will more biomass be needed for energy generation, but also will less fossil energy be available as input to produce biomass, i.e. the price of these inputs may increase. To understand the impact of changing energy use on biomass production, a sound understanding of energy efficiencies in biomass production is indispensable.

Energy efficiency in biomass production first attracted attention in the context of the oil price shocks in the 1970s, when the dependence of food production on fossil fuels was analyzed (Leach, 1976; Odum, 1973; Pimentel et al., 1973; Stanhill, 1974). Interest in energetic efficiencies of biomass production declined in the 1980s (Jones, 1989), but recently the topic gained attention again due to concerns over peak oil and global climate change (Arrieta et al., 2018; Hall, 2011; Pelletier et al., 2011; Pérez Neira et al., 2018). A major finding of studies on agricultural energetics was that increases in land productivity and food production in the course of the green revolution came at the expense of energetic efficiency, or declining energy returns on investments (EROIs) (Cleveland, 1995; Hatirli et al., 2005; Steinhart and Steinhart, 1974). More recent research has shown that efficiency gains in crop production have been achieved during later stages of the green revolution (Pellegrini and Fernández, 2018). However, results at the country or crop scales yield mixed results, identifying increasing efficiencies in some cases, and decreasing or stable efficiencies in others (Arizpe et al., 2011; Hamilton et al., 2013; Pracha and Volk, 2011).

The recent interest in energy efficiency of biomass production has not only addressed food, but even more so the production of biofuels. The major question here was "do biofuels provide significantly more energy than they require for production and processing?". The answer to this question is usually yes, though energy returns are much lower than for fossil fuels (Farrell, 2006; Hammerschlag, 2006). According to a review by Solomon (2010), EROI values presented in different studies range between 1.1 and 1.65 for corn ethanol and 4.4 to 11 for cellulosic ethanol, with the exception of a study by Pimentel and Patzek (2005) who arrive at much less optimistic estimates. Differences in these results show the limited comparability of different assessments, owing to methodological and conceptual challenges in agroecosystem energy accounting related to system boundary choices (Atlason and Unnthorsson, 2014; Giampietro et al., 1992; Murphy et al., 2011).

So far, most research has focused on the energetic efficiency of biomass production for either food or energy provision. In order to explore the fundamental interrelations of energy efficiency and biomass provision for both food and energy, a more comprehensive approach is required. At the level of regional agroecosystems, a recent methodological proposal (Galán et al., 2016; Tello et al., 2016) enables to study long time periods in order to trace shifts from biotic to fossil energy carriers and their effects on land-use intensification strategies, i.e. the socio-ecological transition (Fischer-Kowalski and Haberl, 2007). A number of regional long-term case studies have applied this method (Cunfer et al., 2018; Gingrich et al., 2018b; Parcerisas and Dupras, 2018; Marco et al., 2018). They displayed that the shift towards fully industrialized agriculture was accompanied by both increasing external energy inputs and stable internal energy fluxes within the regional agroecosystem, mainly feed and litter (Gingrich et al., 2018a).

Comprehensive national-scale assessments of agroecosystem energy efficiency change have been conducted only for the cases of Spain (Guzmán et al., 2018) and, with a different accounting framework, France (Harchaoui and Chatzimpiros, 2018). Here we present a new national-scale assessment of agroecosystem energetics for the case of Austria over a 180-year period (1830–2010), covering the transition from a traditional organic to an industrialized land-use system of a Central European country. We advance agroecosystem energy accounting to trace the effects of both agricultural modernization and shifts in biomass production on agroecosystem energetics. Three periods of major land-use intensification strategies are identified and discussed against changes in ecosystem pressures and shifts in social metabolism, making use of extensive existing literature on Austria (e.g., Krausmann, 2001; Gingrich et al., 2016). Conclusions are drawn for future sustainable food and energy provision.

2. Methods, data and case study

2.1. Agroecosystem energy flows and their socio-ecological context

This study adopts the approach of socio-ecological metabolism and investigates biophysical exchange processes between society and the environment, as well as associated changes in environmental pressures (Gonzalez de Molina and Toledo, 2014; Haberl et al., 2006). The empirical core of this study is an analysis of annual national agroecosystem energy flows for the case of Austria in the period from 1830 to 2010. We quantify inputs to, outputs from and recycling fluxes within the national agroecosystem, defining the agroecosystem as the sum of all biomass production processes, i.e. crops, livestock products and wood. For the total agroecosystem we assess biomass reused within the agroecosystem and external (societal) energy inputs (Galán et al., 2016; Tello et al., 2016). The inputs to the agroecosystem are disaggregated into biomass, labor and modern energy inputs (Fig. 1a). In addition to this analysis of the agroecosystem as a whole, we decompose it into its three major components agricultural land, livestock and forest (Gingrich et al., 2018b), and quantify the amount of energy exchanged between them (Fig. 1b). By disaggregating different types of inputs and outputs, and changes in fluxes among the compartments of the agroecosystem, we are able to identify different intensification strategies through time.

Based on the different kinds of inputs displayed in Fig. 1a, we establish three energy efficiency indicators, or Energy Return on Investment (EROI) ratios:

$$\text{Energy Return on Modern Inputs (EROMI)} = \frac{\text{Final Produce}}{\text{Modern Energy Inputs}} = \frac{\text{Final Produce}}{(\text{Fuels} + \text{Fertilizers} + \text{Electricity})} \quad (1)$$

$$\text{Energy Return on Labor Inputs (EROLI)} = \frac{\text{Final Produce}}{\text{Labor Inputs}} \quad (2)$$

$$\text{Energy Return on Biotic Inputs (EROBI)} = \frac{\text{Final Produce}}{\text{Biotic Inputs}} = \frac{\text{Final Produce}}{(\text{Biomass Reused} + \text{Biomass Imports})} \quad (3)$$

EROMI (Eq. (1)) divides final produce (crops, wood, and livestock products; see definition below) by modern energy inputs from fuels and machinery use, fertilizer and electricity. This indicator is similar to that of studies on the fossil-fuel dependence of agriculture

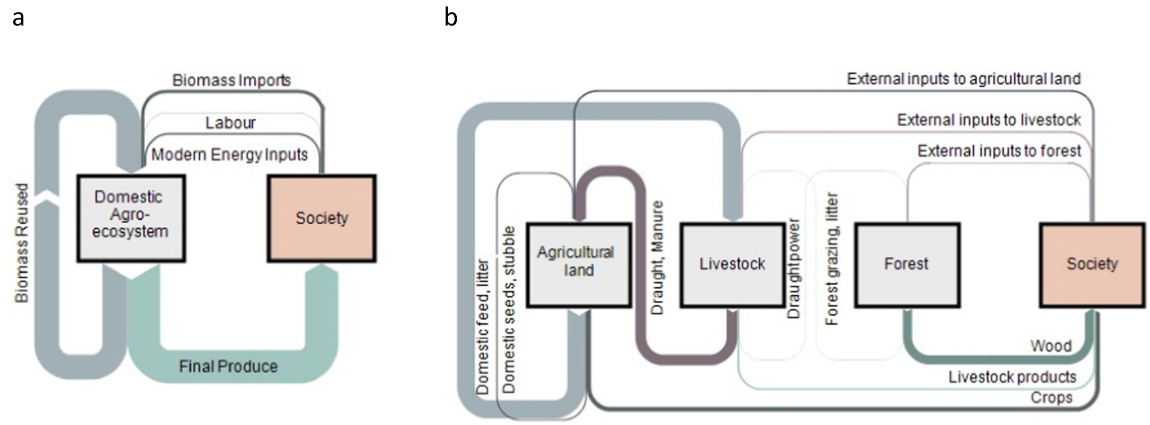


Fig. 1. Energy fluxes quantified between agroecosystems and society in different levels of aggregation (heat and other energy losses were not quantified): a. different types of energy inputs into the agroecosystem as a whole; b. total energy fluxes into, out of and among the three compartments of the agroecosystem: agricultural land, livestock and forest.

(e.g. Arizpe et al., 2011). However, many other studies consider only specific crops, or include food processing, while very few include forest production in their analysis. EROLI (Eq. (2)) is the ratio of final produce to labor Inputs. This ratio is often used in energetic analyses of agroecosystems, but some divergences exist as to how to account for labor. EROBI (Eq. (3)) finally divides final produce by the sum of biotic inputs, including biomass reused (domestic feed, litter, seeds and stubble ploughed into soils[1]) and feed imports. This indicator is similar to the "Internal Final EROI" indicator proposed by Galán et al. (2016) and Tello et al. (2016), describing the amount of final produce generated per unit of biomass reused within the agroecosystem. However, by including biomass imports here, we are able to isolate modern from biotic inputs, which differ in terms of their environmental impacts.

Similarly, for individual years, we calculated the ratio of final produce from agricultural land, livestock, and forests, to the respective total inputs to each of these compartments, as they are denoted in Fig. 1b, establishing EROI values for agricultural land, livestock and forests. For both livestock and agricultural land, this approach is more inclusive than what is often used in the literature on energy agricultural returns on investment (e.g., Hamilton et al., 2013; Markussen and Østergård, 2013; Ozkan et al., 2004). In accordance with more comprehensive approaches (Galán et al., 2016; Tello et al., 2016) we here include biotic energy inputs not related to monetary exchange such as grazed biomass, litter use, and manure use. In addition, we add not only inputs for final production, but also inputs required for the production of non-final products (e.g., fertilizer used to produce fodder designated for the livestock compartment is considered an input to agricultural land). The combination of these two factors makes our EROI values much lower than those in the literature focusing on individual crops, even if biotic inputs are included (Arrieta et al., 2018).

We link the analysis of agroecosystem energy fluxes to changes in social metabolism and ecosystem functioning in Austria. In order to describe social metabolism, we use the following indicators: (1) technical energy use, i.e. the fraction of Domestic Energy Consumption (DEC) used for energetic purposes other than food or feed, i.e. fuelwood, coal, crude oil, natural gas, and electricity (Haberl et al., 2004); (2) CO_2 emissions from fossil fuel combustion; (3) the share of fuelwood in technical energy use. All of these indicators are available for Austria in long time series for the study period from previous work by the authors (Gingrich et al., 2011; Krausmann and Haberl, 2007), and were updated for this study to 2010. The ecosystem impacts are discussed based on (1) ecosystem carbon stocks, i.e. the sum of carbon permanently stored in terrestrial ecosystems and soils (Gingrich et al., 2016), and (2) the Human Appropriation of Net Primary Production (HANPP), i.e. the share of potential annual ecosystem primary production which is appropriated through society (Haberl et al., 2014), either through biomass extraction or through land conversion (Gingrich et al., 2015). In addition to these indicators, we discuss the newly-assessed indicator "self-fueling", which is estimated based on the agroecosystem energy fluxes described above, but follows slightly different system boundaries. Self-fueling describes the ratio of agricultural final produce (i.e. total final produce minus wood) to the energy required for providing labor and draught power (Harchaoui and Chatzimpiros, 2018). Finally, we present modern energy inputs to agroecosystems as a fraction of total technical energy use.

[1] Manure is not considered part of biomass reused, because this would result in double counting the energy in feed and litter use. Manure flows are assessed in the disaggregated analysis.

2.2. Data, sources and accounting procedures

Data on long-term changes in Austrian land use, biomass extraction and structural agricultural change were compiled from national and provincial statistical periodicals by Krausmann (2001), Krausmann and Haberl (2002) and Gingrich et al. (2016) and updated and expanded in the context of this study. For detailed descriptions of the sources used, please refer to these previous studies. Here we focus on the basic aggregation and accounting procedures used to generate the energy fluxes and EROI indicators from this database, and describe in more detail the estimation of energy inputs to agroecosystems which have previously not been assessed.

Final produce is defined here as the sum of final biomass products aimed at domestic human consumption or export, including round wood, livestock products, and crops (Galán et al., 2016; Tello et al., 2016), but excluding those biomass fluxes reentering the agroecosystem such as feed and fodder, seeds, litter and stubble ploughed into soils. Final produce was estimated based on appropriate allocation of previously-compiled biomass extraction and production data which were converted into energy (Haberl, 1995). For wood, all extraction of firewood and timber was considered final produce. Particularly in the early 19th century, wood extraction is rather poorly documented (see Krausmann, 2001). Livestock products were assessed based on statistical reports of meat, milk and egg production, or on livestock numbers and species-specific productivity (before 1910). Final production of crops was quantified by subtracting fodder and seeds, both derived from national food balances from 1934 onwards, from total crop production reported in agricultural statistics. For the period prior to 1934, both fodder and seed use was accounted by applying the crop-specific share of production from 1934.

Biomass reused is defined as the consumption of domestic feed and fodder, grazed biomass and litter, as well as seeds and aerial biomass ploughed into soils (Galán et al., 2016; Tello et al., 2016, Fig. 1a). Feed intake and composition, as well as litter use, were assessed based on a combined supply and demand approach (Gingrich et al., 2016; Krausmann, 2001): Feed demand was estimated for all livestock species, considering increases in live weight and productivity over time. Fodder production, feed imports, straw not used as litter and other edible by-products like beet leaves were subtracted from feed demand, and the remainder was assumed to be grazed directly by animals. To account for litter use as bedding material, species-specific litter demand values (Beer et al., 1990; von Lorenz, 1866) were multiplied by livestock numbers. Forest litter (leaves, branches used as bedding material) was assumed to be used throughout the 19th century and, in declining amount, until the mid-20th century (Krausmann, 2001).

External energy inputs comprise labor applied in agriculture and forestry, imports used to feed the domestic livestock as well as modern energy inputs, including mineral fertilizers, fuels for machinery, and electricity applied in agriculture. Labor is defined here as the gross food energy intake required to feed agricultural and forest workers during their labor time (Galán et al., 2016; Tello et al., 2016): In a top-down approach we calculated the amount of expended labor time based on data of agricultural population and average work time. The results were cross-checked in a bottom-up approach: we used crop- and livestock-species specific information on work time demand from Hitschmann (1891) for the 19th century and Handler et al. (2006) and Greimel et al. (2002) for the 21st century to generate information on the labor time demand of land and livestock management at specific time points. In accordance with Darge (2002) offering estimates for 1950 to 1995, gross food intake of 1.2 (1830) to 0.8 MJ/h (2010) was applied in the period, considering the declining physical effort required due to mechanization.

For all external inputs, the embodied energy was assessed. For mineral fertilizers, we multiplied data on fertilizer use available from agricultural statistics by time-specific energy demand for fertilizer production (Aguilera et al., 2015). Early mineral fertilizers like potash, guano and others played a very minor quantitative role in Austria (Mayrhofer, 2014) and were not considered in the accounting. Similarly, pesticide application was not accounted due to its minor contribution to energy inputs (Gingrich et al., 2018b). Energy use in agricultural machinery was estimated based on agricultural diesel use documented in national energy balances since 1970, and extrapolated back into the past based on tractor numbers and the average annual diesel use per tractor of 1970. Embodied energy in diesel generation and transport, as well as in machinery production, was assessed using factors from Aguilera et al. (2015). Data on electricity use in agriculture are also available from national energy balances since 1970. Electricity use prior to 1970 was extrapolated based on numbers of milking machines reported in agricultural statistics, which were considered as proxy for the degree of electrification in livestock management, the major electricity consumer in Austrian agriculture (Kränzlein and Mack, 2007). Energy embodied in electricity generation was estimated by applying factors provided in Aguilera et al. (2015), using the Austrian electricity mix available from national energy balances. Fodder imports were derived from Austrian foreign trade balances, available since 1951, and energy embodied in transport and processing was assessed using values from Marco et al. (2018).

Additional energy fluxes were assessed to understand energy inputs of manure and draught power from livestock to agricultural land and forests (Fig. 1b), and to quantify EROIs for the three compartments of the agroecosystem. Energy in livestock excreta was assumed to roughly amount to 40% of feed intake in 1830 and 35% in 2010, considering changes in species composition and conversion efficiency (Jeroch et al., 2008). Manure was assessed as the sum of excreta plus bedding material input (see above). Draught power was estimated as share of feed intake, based on the fraction of time used for draught. For the period before the use of tractors, i.e. 1830–1929, this estimate was based on time demand assessments for draught power on different land-use categories (Hitschmann, 1891). In the period 1930–1978, when both tractors and draught animals were reported, we applied an average time demand of 21% to the total time availability of the respective number of draught animals.

Overall, we consider the data used as rather robust, in particular since the mid-20th century. We carried out a sensitivity analysis in order to assess the effect of variations in the least reliable input data during the 19th and early 20th centuries, i.e. forest harvest, labor and livestock production (see SOM). We also assessed the effect of differing accounting choices regarding (1) the inclusion of belowground biomass in biomass reused and (2) a re-definition of final produce as "socialized biomass" as it is proposed by Guzmán et al. (2018), see SOM.

2.3. Description of the case study

Austria is a Central European country of 84,000km^2, which has, in its current boundaries, existed since 1923. In the study period before this time, those provinces of the Habsburg Empire matching today's national boundaries closest were aggregated to generate a comparable territorial unit (Krausmann and Haberl, 2002). Austria's climate is temperate, and the topography is dominated by the Eastern Alps, covering almost a third of the national territory. In the Alpine regions, forests and grasslands are the major land cover classes. Crop production concentrates in the prealpine lowlands.

In the course of the study period, the Austrian economy industrialized, and in 2016 the average income was 50,503 US$/cap and year, according to OECD Data (https://data.oecd.org). Agriculture underwent substantial changes in the past 200 years, including yield increases, mechanization and a decrease of agricultural population (Table 1). Compared to other European countries, such as e.g. Germany or France, land use in Austria is rather extensive, owing to the steep topography fostering forestry dominated by spruce (*Picea abies*), as well as grassland-based cattle farming. Average farm size is small in European comparison, amounting to 19.7 ha of agricultural and forestry land per farm in 2016, according to the most recent Austrian agricultural structure assessment by Statistik Austria.

3. Results: Energy flows in the agroecosystem and its compartments

Austrian agroecosystem energy fluxes by main types are depicted in Fig. 2 for the period 1830–2010. Overall, final produce more than doubled from c.150 PJ/yr in 1830 to over 300 PJ/yr in 2010. Final produce was dominated by forest products throughout the period, their share ranging between 71% in the mid-20th century and 89% in the early 19th century. The trend in wood extraction also determined the overall trend in final produce, though the decline in forest extraction in the late 19th century can not be viewed as robust, see SOM. From the 1970s onward, forest extraction increased significantly, contributing to a doubling of final produce between 1975 and 2010.

The strong dominance of forest products in final produce conceals important trends in agricultural final production. Final products from cropland, i.e. mostly vegetal food, increased from 11 PJ/yr in 1830 to 47 PJ/yr in 2010, and livestock final products, i.e. meat, milk and eggs,

Table 1
Basic characteristics of land use in Austria, 1830–2010, based on the data and sources described above.

	1830	1914	1986	2010
Cropland [% land area]	25	26	18	17
Grassland [% land area]	29	27	23	21
Forest [% land area]	37	39	46	48
Livestock density [LSU/ha agricultural land]	0.3	0.6	1.0	0.8
Cereal yields [kg/ha]	890	1408	4006	4309
Agricultural and forest workers [1000 cap]	1518	1368[a]	224	159
Tractors [1000 pieces]	–	0.7[b]	326	332
N fertilizer use [kg/ha agricultural land]	–	0.4[c]	62	43

[a]Value refers to 1910; [b]Value refers to 1930; [c]Value refers to 1925.

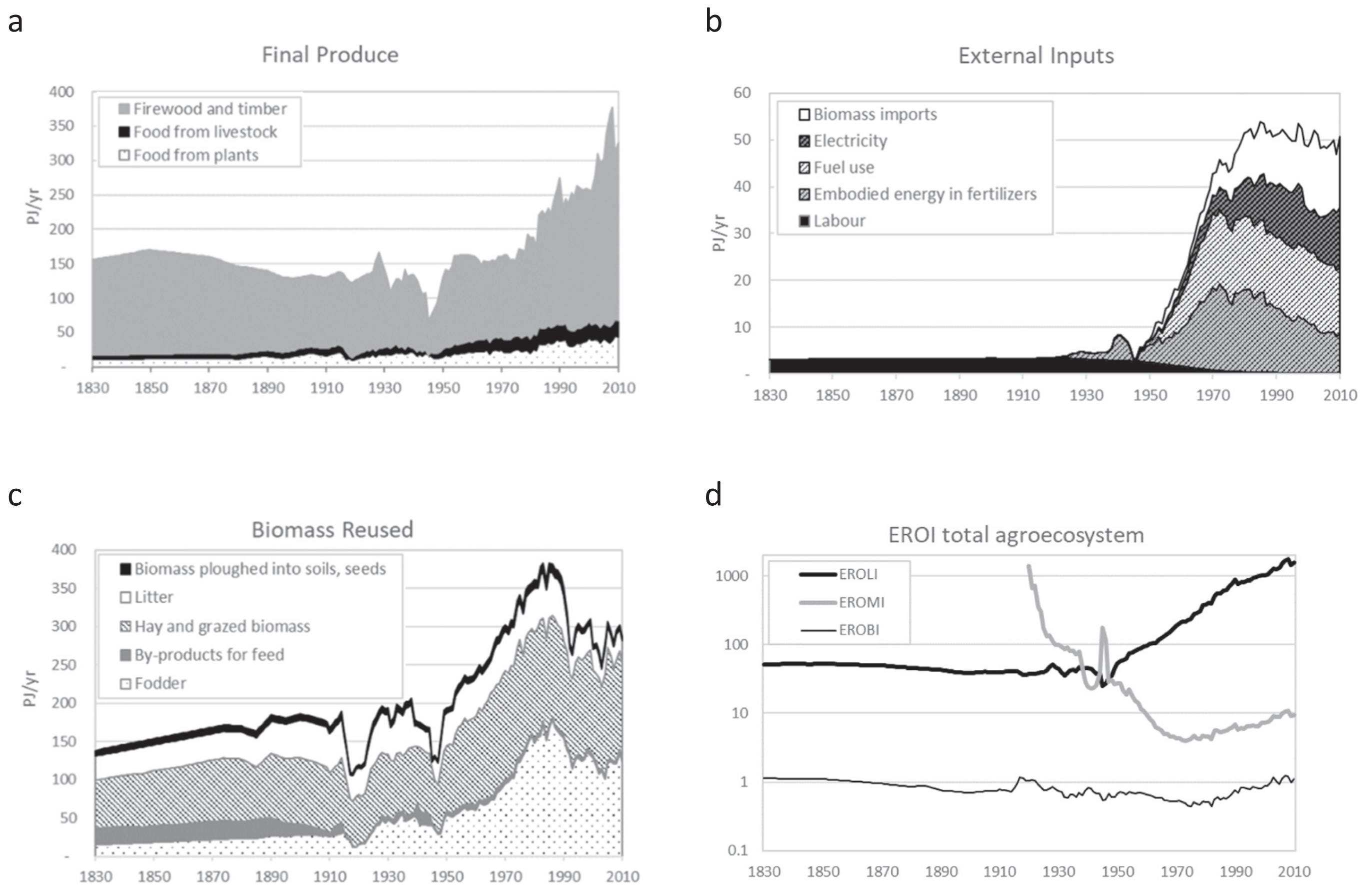


Fig. 2. Major agroecosystem energy fluxes and ratios through the Austrian agroecosystem as a whole. (a) Final produce, (b) external inputs, (c) biomass reused, and (d) Energy Returns on Investment (EROI), distinguishing Energy Return on Biotic Inputs (EROBI), Energy Return on Modern Inputs (EROMI), and Energy Return on Labor Input (EROLI).

grew from almost 6 PJ/yr to 24 PJ/yr. Both variables, thus, increased by a factor of more than 4. These changes are the result of massive intensification of both agricultural land use and livestock production: Cropland final produce per unit of agricultural land increased almost by a factor of 6 from 5 GJ/ha/yr in 1830 to 31 GJ/ha/yr in 2010, allowing for increases in total crop production while agricultural land area declined. The rising output of final produce per unit of land was a result of both growing yields (see Table 1) and, more recently, increases in the share of final produce to total biomass production from agricultural land, i.e. less products fed to the domestic livestock. For livestock, productivity increases were less pronounced, but significant nevertheless: the amount of energy in animal products per livestock unit increased by a factor 2.3 between 1830 and 2010, from 4.0 GJ/LSU/yr to 9.1 GJ/LSU/yr. Temporal trends in crop and livestock final produce slightly differed in the second half of the 20th century. In the decades after World War II, livestock and cropland final produce converged until the early 1980s when they were equal at around 20 PJ/yr. Only in recent decades did livestock production stagnate while livestock numbers declined. Output of final crop products, in contrast, continued to increase.

External inputs to the agroecosystem display a very distinct temporal trend (Fig. 2b), similar to that of other European countries like Spain and France (Guzmán et al., 2018; Harchaoui and Chatzimpiros, 2018). External inputs were very limited throughout the 19th and early 20th centuries, the only major input being agricultural labor (bear in mind that draught power is not accounted as external input here). Between 1830 and the onset of World War I, labor inputs into agroecosystems increased by c. 10%, resulting from increases in livestock numbers and, to a lesser extent, shifts to more labor-intensive crops, such as potatoes. In the 1920s, synthetic nitrogen fertilizers started to be used, doubling external energy inputs during the interwar-period. After World War II an entirely new dynamic set in: In only three decades, from 1950 to 1980, external inputs increased by a factor of 7, from 7 PJ/yr to 50 PJ/yr, while labor inputs slumped. The growth in inputs was the result of increasing fertilizer and fuel use in machinery until 1970, which then accounted for 78% of external inputs. From 1970 to 1980, rising biomass imports (mainly protein feed) and agricultural electricity use overcompensated the decline in fertilizer use, while fuel use stagnated. Since 1980, total external energy inputs remained at a level of around 50 PJ/yr, and even declined slightly, mostly because fertilizer input further went down.

The third major energy flow is biomass reused, i.e. feed, litter, seeds and crop residues ploughed into the soil (Fig. 2c). In Austria, the annual flow of biomass reused is comparable in size to that of final produce. Biomass reused would be about 15% higher if belowground biomass was included, see SOM. Throughout the entire period, the largest part (over 95%) of this energy flow entered the livestock system. Seeds and crop residues ploughed into soils accounted for less than 5% of biomass reused (note that manure is not accounted as part of this flow, but will be discussed separately below). Over time, the amount of biomass reused entering the livestock system coarsely followed the changes in livestock numbers and ranged between 60 and 115 GJ/LSU/yr. Changes in the amount of biomass reused per livestock unit are due to variations in species composition (e.g., pigs using less than cattle), and changes in management over time. The most important temporal trend in biomass reused was an increase in fodder crops, comprising market feed and forage crops. Fodder crops peaked in 1986 at 47% of total biomass reused and later declined with the reduction in livestock numbers and with increasing fodder imports.

The described changes in agroecosystem inputs and outputs translate into changing energy returns of investment (Fig. 2d). Since biotic inputs (biomass reused plus biomass imports) make up for the largest fraction of energy inputs, energy returns on biotic inputs (EROBI) were lowest throughout the time period. EROBI declined from the beginning of the period (value of 1.1), however the trend during the 19th century is highly dependent on the uncertain information on wood extraction, and can not be considered reliable (see SOM). During the early 20th century, EROBI further declined and reached a minimum in the 1980s at 0.4. Since then, caused by increases in forestry production and a decline of livestock numbers (Table 1), EROBI has increased again, surpassing 1 in 2003. Energy returns on labor inputs (EROLI) were much higher than EROBI, and display a much more distinct temporal trend: EROLI declined slowly since the mid-19th century from c.54 to values below 40 in the interwar period, due to continuously declining wood harvest and growing livestock numbers. Again, we consider this decline as not robust due to uncertainties in wood harvest data (SOM). After World War II, EROLI increased exponentially with rapidly declining labor input at increasing final produce, and reached values around 1500 in the 21st century. Energy returns on modern inputs can be quantified since the first major modern energy inputs were used in the interwar period. In the initial years, the new technologies still consumed very little energy and EROMI rapidly declined to values around 100 in the 1930s, with disruptions due to fertilizer shortage in the 1940s. From 1945 to the early 1980s, modern inputs replaced human labor, resulting in diverging trends of EROMI and EROLI. EROMI declined to around 4.5 in the 1980s, because modern energy inputs increased more strongly than final produce. Since then EROMI recovered to values above 10, in part explained by increases in forest production, but also by increased fertilizer use efficiency.

Fig. 3 displays energy fluxes among the agroecosystem compartments agricultural land, livestock and forests, for four points in time representative of peaks in specific trends. Between 1830 and 1914 (Fig. 3a and b), the most important change in absolute numbers was a decline in wood extraction, which, again, can not be considered as robust. Both crop production for human consumption and livestock production doubled in this period, owing to increases in numbers and productivity of livestock, as well as shifts in the species mix (less sheep, more pigs). Increasing livestock production also resulted in growing manure use by 50% from 1830 to 1915. This in turn allowed for replenishing soil fertility, increasing fodder production and further raising livestock production. Improvements in livestock management were thus a crucial factor in the intensification of the pre-industrial, or "advanced organic" land use system. However, the growing livestock sector had negative effects on total agroecosystem energy returns on investment, as discussed above.

Throughout the mid-20th century, livestock draught power applied in agriculture or forestry was replaced by machinery, while mineral fertilizers added to manure output on agricultural land. At the peak of agricultural industrialization in the mid-1980s, external inputs to the agroecosystem were highest, and energy return on modern energy inputs (EROMI) was lowest. Fig. 3c shows however that domestic feed and fodder production still played a major role in industrialized Austrian agriculture of the 20th century, and the manure generated by livestock was continuously used to fertilize agricultural land. Energy fluxes from agricultural land to the livestock sector (feed and litter), as well as fluxes from livestock back to agricultural land (manure, but no more draught power) were in fact much greater than societal energy inputs to or products from either agricultural land or livestock. Only wood harvest was comparable in magnitude to these flows. Finally, by 2010 (Fig. 3d), the shift of livestock production from cattle towards pigs resulted in declining energy fluxes between livestock and agricultural land, at stable livestock production. At the same time, more crop products were directed towards societal use. The increase in wood extraction

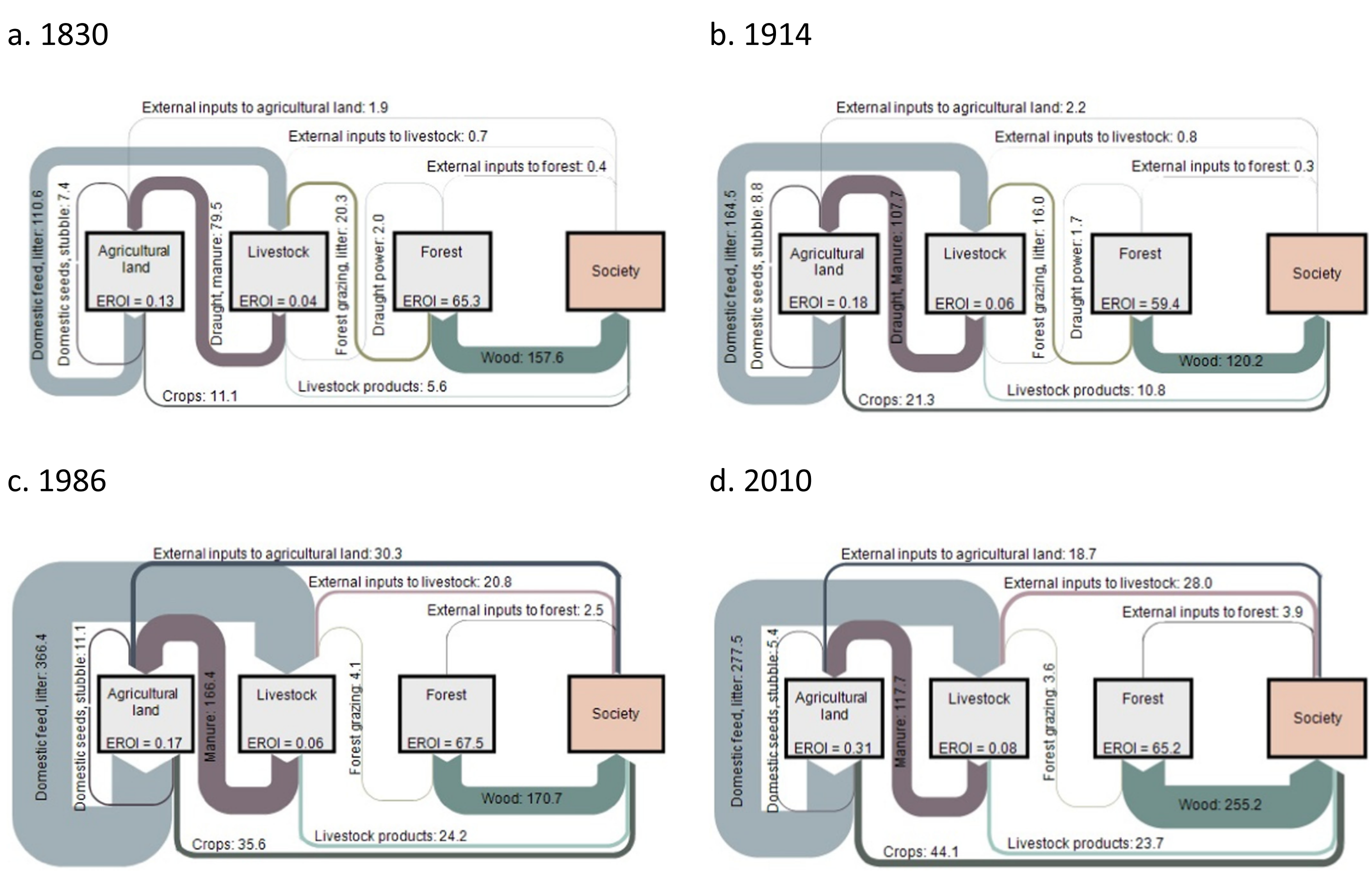


Fig. 3. Agroecosystem energy fluxes among society and three compartments of the agroecosystem (agricultural land, livestock, forest). Arrow width reflects the extent of the flow, values of individual flows are in PJ/yr. In each of the agroecosystem compartments, the ratio of final produce to total inputs is provided.

in this period occurred in a way independently from these processes, but contributed greatly to increasing energy returns at the total agroecosystem level.

The ratios of final produce from the three compartments to the respective total energy inputs into each compartment are presented in the respective boxes in Fig. 3a–d. Wood production was clearly the most energy efficient activity, albeit producing energy not suitable as food. Forest EROI values remained almost stable throughout the period, ranging between 59.4 and 67.5. In livestock management, EROI values were lowest throughout the period, but more dynamic, increasing from 0.04 in 1830 to 0.08 in 2010. Crop production was most dynamic, with values of 0.13 in 1830 and 0.31 in 2010. In both crop and livestock production, efficiency changes were linked to changes in the quality of inputs (e.g., fertilizing improvements, shifts to higher quality fodder), shifts in the composition of production (e.g., more corn, more pigs), as well as better conversion efficiencies of individual species. In addition, for the case of agricultural land, the share of products used for domestic fodder influences the amount of final produce designated for human consumption and export. This analysis shows that efficiency gains were achieved in all types of production, but temporal trends in overall EROI values were more determined by changes in the composition of final produce. While changes in EROIs in individual production types ranged from close to zero (forestry) to a factor 2.4 (crop production) between 1830 and 2010, the difference between EROIs of the most and least energy efficient management practices (forestry and livestock production) reached values up to c. 1500.

The differences among types of biomass production are important for understanding (1) possible regional divergences within Austria, and (2) the specificities of the Austrian case. (1) Contrasting previous regional assessments of agroecosystem energy efficiency for Austria (Gingrich et al., 2018b), the national total displays the high importance of forestry. Given the increasing regional diversification of land-use distribution within Austria since World War II (Krausmann et al., 2003), we may assume that regional EROMI and EROBI values also diverged, particularly since the 1950s. EROBI and EROMI must have declined in the prealpine regions where livestock production gained in relative importance, and increased in regions where forests or cropping became more dominant, i.e. in the mountainous regions where considerable reforestation occurred, as well as in the crop producing regions in the Eastern part of the Danube Basin.[2] (2) As compared to Spain (Guzmán et al., 2018), Austrian "Final EROI" (final produce divided by total inputs consumed) was higher throughout the 20th century. In 2008, Final EROI in Spain was 0.72, compared to 1.1 in Austria. This is only partly due to accounting differences (see SOM). More relevant was the differing composition of final produce. In Spain, animal products, which depended to a greater share on feed imports (Soto et al., 2016), were much more relevant (c. 25% of final produce as opposed to 6% in Austria). Wood products on the other hand played a minor role in Spain (c. 15% of final produce in Spain and 83% in Austria), despite growing forest areas in both countries.

4. Discussion: three distinct periods of land-use intensification

In this analysis we advanced agroecosystem energetic accounting to trace long-term changes in energetic efficiencies for the case of Austria at an annual resolution. Our aim was to establish a consistent indicator framework depicting the entire agroecosystem while enabling to disaggregate various fluxes and compartments within the agroecosystem. Thus, changes of energetic efficiency in the entire national agroecosystem could be traced, while disentangling effects of shifts in final production (i.e. crops vs. livestock products vs. forestry) from actual efficiency gains within these production types.

The EROI indicators we applied inform about different types of energetic efficiency from an agronomic standpoint, by comparing final production to different types of energy inputs (Guzmán et al., 2018). The indicators do however not contain information on the ecological sustainability of land use. In fact, high EROI values during a certain time period may be the result of unsustainable use, e.g. during processes like deforestation or soil mining. In order to trace the sustainability challenges of different land-use strategies, we now discuss our results against long-term trends in social metabolism and ecosystem characteristics. For this purpose, we identify three periods of distinct land-use intensification strategies according to temporal trends in agroecosystem energy fluxes. These periods match, but are slightly coarser than the periodization presented in Jepsen et al. (2015): (1) pre-industrial land-use intensification (1830–1914), (2) industrialization of land use and the green revolution (1920–1985), and (3) industrialized extensification and environmental awareness (1986–2010).

We argue that these periods are stages of the socio-ecological transition (Fischer-Kowalski and Haberl, 2007; Krausmann et al., 2008), during which the significance of biomass for social metabolism changed, and the impacts of land management on ecosystems changed too. Table 2 presents the indicators used to characterize ecosystem features and social metabolism in these periods.

4.1. Pre-industrial land-use intensification

Throughout the 19th and early 20th centuries, land-use intensification in Austria resulted in growing agricultural but declining forestry output, at the expense of declining system-wide EROIs. The most relevant intensification process was increasing livestock production. The effects of land management on ecosystem productivity were significant: the share of net primary productivity appropriated by society (HANPP) was higher than in any other period, ranging above 60% until the 1910s. Ecosystem carbon stocks amounted to c. 1050 MtC in this period, or 52% of those of potential vegetation (Erb, 2004). Ecosystem carbon stocks remained stable through much of the period, and slightly increased towards the end of the 19th century, linked to changes in societal energy use (Erb et al., 2008).

In this period, technical energy use was lower than in any other period. Firewood dominated technical energy use at first (99% in 1830), but was increasingly supplemented by coal towards the end of the 19th century (still 75% in 1867, but only 12% in 1914). The increase in coal consumption allowed for growing energy supply at declining fuelwood use. The increase in coal use resulted in rising CO_2 emissions from fossil fuels, surging from 0.06 Tg/yr in 1830 to above 28 Tg/yr in 1914. These changes affected the output of agroecosystems by reducing pressure on forests to provide wood. However, they did not impact energy inputs to agroecosystems significantly: tractors and chemical fertilizers were not available yet, and agriculture was intensified mostly through increased domestic, mostly on-farm biotic energy inputs. The amount of biomass required for labor and draught power ("Self-Fueling") in this period made up almost half of final produce (47%). This illustrates the high dependence of the agricultural sector on biotic energy sources.

4.2. Agricultural industrialization and the green revolution

Soon after World War I, a new dynamic of land-use intensification set in: Starting in 1920, the use of synthetic fertilizer was reported in Austria, and in 1930, the first tractors appear in agricultural statistics. After World War II also fodder imports and electricity added to energy inputs. While all these inputs remained low in numbers during the first decades of this period, they triggered a new trajectory of land-use intensification. Particularly after World War II, outputs of crops, livestock products, and wood grew rapidly. While energy returns on

[2] Note that the spatial scale of the region of analysis has an impact on EROI indicators: The increase in EROMI and EROBI in cropping-dominated regions will further be amplified at local or regional scales because in smaller spatial units, a higher share of biomass production will be considered final produce. Comprising all marketed biomass means that at the regional scale, fodder crops or straw sold outside the region under investigation would be allocated to final produce, while at the national scale this would be considered biomass reused.

Table 2
Indicators of ecosystem pressure and social metabolism during major periods of agroecosystem energetic change. Sources: see Methods, data and case study section.

	Pre-industrial land-use intensification (1830–1914)		Industrialization of land use and the green revolution (1918–1985)[a]		Industrialized extensification and environmental awareness (1986–2010)	
	Average value	Average annual growth rate	Average value	Average annual growth rate	Average value	Average annual growth rate
Human appropriation of Net Primary Production [% of potential Net Primary Production]	62	−0.09%	52	0.29%	55	0.18%
C stocks in vegetation and soils [Mt C]	1050	0.03%	1138	0.16%	1243	0.25%
CO_2 emissions from fossils [kt Co_2/yr]	9010	8%	33,029	3.7%	65,738	1.1%
Technical energy use, i.e. Domestic Energy Consumption used for energetic purposes other than food or feed [PJ/yr]	194	1.4%	533	8.9%	1260	1.5%
Fuelwood in technical energy use [%]	60	−2.4%	12	−2.4%	7	−0.7%
Self-Fueling [% of energy for labor and draught in agricultural final produce]	47	−0.8%	18	−3.4%	0.5	−3.1%
Modern energy inputs to agroecosystems [% of technical energy use]	–	–	2.2	11%	3.1	−2%

[a] In this period, we exclude the years 1938–1947, due to lack of reliable data during the years of World War II and immediately afterwards.

modern, as well as biotic energy inputs declined, energy returns on labor increased during this period. These changes were linked to a fundamental alteration in ecosystem characteristics and socio-economic metabolism.

Despite the increasing extraction of biomass from ecosystems, Human Appropriation of Net Primary Production in this period was distinctly below the values of the 19th and early 20th centuries, at levels around 52% of potential NPP. Paradoxically, this was made possible in particular through the intensification of croplands, which raised the productivity of actual vegetation, enabling increasing extraction at declining levels of HANPP (Gingrich et al., 2015; Krausmann, 2001). In addition, C stocks in ecosystems increased, an effect of both forest expansion and vegetation thickening (Gingrich et al., 2007). Other ecosystem impacts of course increased in this period: For example, the use of mineral fertilizers (N, P and K) grew dramatically from less than 1 kg/ha/yr of pure nutrient application per unit agricultural land in the 1920s to over 60 kg/ha/yr in the mid-1980s, affecting soil and water (Katzmann et al., 1991; Tollmann, 1991). In addition, the combination of agricultural intensification in favorable regions (Krausmann et al., 2003), and agricultural abandonment of less suitable areas resulted in a loss of biodiversity (Niedrist et al., 2009). Still, in terms of the ratio of biomass extraction to ecosystem biomass productivity, some pressure was taken from the land, resulting in a recovery of biomass stocks in ecosystems.

We attribute this to changes in social metabolism: in the period after WWI, energy was more and more abundantly available, with crude oil becoming the most important energy carrier in the early 1960s. Crude oil not only substituted for coal in households and industries (Krausmann and Haberl, 2002), but as fuel used in internal combustion engines it also replaced human and animal labor in agroecosystems. This is reflected in the declining degree of self-fueling of Austrian agriculture: While in 1918, food for labor and feed for draught power still amounted to 21% of agricultural final produce, this share declined to 1% in the mid-1980s. The shift from coal to crude oil (and, to a lesser extent, to natural gas and electricity), led to a declining CO_2 intensity of technical energy use. However, the strong increase in technical energy use overcompensated these efficiency gains, and CO_2 emissions from fossils doubled between 1918 and 1986.

Modern energy inputs in Austrian agroecosystems made up only 2.2% of total Austrian technical energy use in this period, but the share grew over the period. Studies considering the entire food system (including processing, packaging, transport, cooling, etc.) demonstrate that the entire food system in industrial countries uses about twice the energy input as agricultural production alone (Kim et al., 2018; Pelletier et al., 2011). Still, this means that while modern energy inputs to agroecosystems greatly transformed agroecological functioning, they were of minor importance compared to energy inputs to other economic sectors.

4.3. Industrialized extensification and environmental awareness

As a response to increasingly cost-prohibitive subsidy schemes triggering intensification and overproduction, Austrian agricultural policy changed fundamentally from 1986 onwards, following the idea of "eco-social agricultural policy" (Riegler, 1988; Schneider and Hofreither, 1988). In 1988 for example, the previously state-guaranteed fixed milk prices were abolished, and financial incentives for alternative crops such as protein feed crops and energy crops were introduced (Hanisch, 2002). In addition, far-reaching agri-environmental schemes were implemented. These measures resulted in a stagnation of livestock production, while cropland production, as well as wood production, increased further. A levy on chemical fertilizer contributed to a more efficient use of fertilizers (Rougoor et al., 2001). According to our data, the ratio of biomass production from agricultural land per unit of pure N use was 2.3 GJ/kg/yr on average in the 1980s and 2.7 GJ/kg/yr in the 2000s, that is an increase by 19%. Other modern energy inputs remained stable in this period. Improvements in energy returns on modern and biotic inputs in this period resulted from both shifts in production and efficiency changes within production types. These changes had ambiguous impacts on ecosystem characteristics, and were not enough to reverse trends of socio-economic metabolism.

C-stocks in ecosystems continued to increase until 2010, while HANPP was, at 55% of potential net primary productivity, somewhat higher than in the previous period. The slight increase in HANPP results from higher wood extraction. The fact that ecosystems continued to act as C sinks (despite the important extraction of wood), may be a delayed effect of previous forest pressure relief. Given that forests grow slowly and thus react to management with a temporal delay of several decades, the short period of time from 1986 to 2010 does not represent the societal impacts on forests during that same period. In fact, in the most recent forest assessment period (2000–2009), wood extraction was higher than forest regrowth in two of three forest ownership types (Büchsenmeister, 2011), indicating that biomass stock increase in Austrian forests may be coming to an end.

Both technical energy use and socio-economic CO_2 emissions were higher in this period than in any other. Annual growth rates in these two indicators were positive but low and, at c. 1.5%/yr and 1.1%/yr, respectively, very similar. Growing energy use and emissions were not compensated for by declining CO_2-intensities per unit of energy used (Gingrich et al., 2011). The increasing extraction and use of wood driven by increasing woodfuel use, which had major implications for energetics within the agroecosystem and for Austria's ecosystem characteristics, was not enough to reverse trends of societal metabolism either by reducing CO_2 emissions in absolute numbers or even by increasing the share of biomass in technical energy use in the long run. Modern energy inputs to the agroecosystem accounted for 3.1% of technical energy use on average in this period, i.e. more than in the previous period, but still a low fraction. This low share of modern energy entering the agroecosystem is contrasted by the fact that labor was in this period to a large degree externalized to machine use, displayed in the low degree of self-fueling of 0.5%.

5. Outlook: implications for future land and energy use

The long-term analysis of agroecosystem energetics in Austria throughout its industrialization process reveals significant insights on the interrelations of energy use and the land-use system. We discuss some general implications for future biomass-based provision of food and energy and its potential environmental impacts.

Regarding food provision, our study confirms that shifts towards less animal-based, more vegetal-based food production have a positive effect on agroecological energy returns on investment. The long-term analysis reveals that such shifts have the potential for greater improvements in energy efficiency than those achieved within livestock or crop production, respectively. According to FAOstat, the Austrian share of animal products in both food production (37%) and food consumption (30%) were well above the global average in 2010 (18%), so reducing animal products in Austrian food production and consumption could contribute importantly to improving agroecosystem efficiency.

The exceeding importance of the livestock sector in Austria's agroecosystems is also exemplified by the extent of energy fluxes entering and exiting the livestock sector. Our analysis reveals that while modern energy inputs multiplied in the course of just a few decades from the 1920s to the 1980s, their highest values were still below the energy fluxes between the livestock sector and agricultural land by around a factor 8. Also compared to total technical energy use, modern energy inputs to agroecosystems were surprisingly small, reaching a maximum of 5% in the late 1960s. In recent decades, decreases of these inputs were met by efficiency gains, when we observe a continuous increase in crop yields per unit of land at strongly declining fertilizer use. While it may be unrealistic to sustain Austria's industrialized agriculture based on renewable energy sources, it seems reasonable that further efficiency gains could be achieved also regarding the use of fuels in tractors, the input of electricity or the use of symbiotic fertilization techniques as opposed to mineral fertilization (e.g., Herridge et al., 2008).

On the other hand, our study displays that increasing energy provision from biomass may be a great future challenge at current levels of societal technical energy use. In the 19th century, when wood was the major technical energy carrier, pressures on Austrian ecosystems were considerable. In recent years, fuelwood extraction has increased significantly, but still contributed only c. 6% to technical energy consumption in 2010. Total wood extraction (including timber) accounted only for 17% of technical energy use in 2010. Increasing fuelwood extraction for climate change mitigation could increase agroecosystem energy efficiency, but would not be compatible with plans to continuously build up ecosystem carbon stocks. Higher biofuel production from agriculture on the other hand, which in 2016 contributed roughly 13% to Austrian technical energy use (Biermayr, 2017), counteracts efforts to extensify crop production.

Our comprehensive, long-term perspective complements previous work on energy efficiency in biomass production for either food (Pellegrini and Fernández, 2018; Pelletier et al., 2011) or energy provision (Hammerschlag, 2006; Solomon, 2010). It displays the changing role of agroecosystem energetics both in the context of ecosystems and social metabolism, and identifies trade-offs and limitations of future transitions to sustainable biomass production and use. Further research studying more and different cases will reveal to which extent findings on Austria can be generalized.

Acknowledgements

We thank three anonymous reviewers for valuable and constructive comments. We gratefully acknowledge support from the Canadian Social Science and Humanities Research Council ("SFS", Partnership Grant 895-2011-1020) and the European Research Council ("HEFT" ERC-2017-STG 757995). This research benefitted from discussions with project partners, as well as participants in the Conference of the European Society for Ecological Economics (ESEE) in Budapest and the Conference of the European Society for Environmental History (ESEH) in Zagreb, both in 2017.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.07.074.

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 (No. 1507), Documentos de Trabajo. 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. https://doi.org/10.1080/07352689.2011.554352.

Arrieta, E.M., Cuchietti, A., Cabrol, D., González, A.D., 2018. Greenhouse gas emissions and energy efficiencies for soybeans and maize cultivated in different agronomic zones: a case study of Argentina. Sci. Total Environ. 625:199–208. https://doi.org/10.1016/j.scitotenv.2017.12.286.

Atlason, R., Unnthorsson, R., 2014. Ideal EROI (energy return on investment) deepens the understanding of energy systems. Energy 67:241–245. https://doi.org/10.1016/j.energy.2014.01.096.

Beer, K., Kotiath, H., Podlesak, W., 1990. Organische und mineralische Düngung. Deutscher Landwirtschaftsverlag, Berlin.

Biermayr, P., 2017. Erneuerbare Energie in Zahlen 2017. Entwicklung in Österreich. Datenbasis 2016. 1 (Auflage. ed. Wien).

Büchsenmeister, R., 2011. Waldinventur 2007/09: Betriebe und Bundesforste nutzen mehr als den Zuwachs. BFW Prax. Inf. 5–9.

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

Cunfer, G., Watson, A., MacFadyen, J., 2018. Energy profiles of an agricultural frontier: the American Great Plains, 1860–2000. Reg. Environ. Chang. 18:1021–1032. https://doi.org/10.1007/s10113-017-1157-x.

Darge, E., 2002. Energieflüsse im österreichischen Landwirtschaftssektor 1950–1995, Eine humanökologische Untersuchung. Social Ecology Working Paper. IFF Social Ecology, Wien.

Erb, K.H., 2004. Land-use related changes in aboveground carbon stocks of Austria's terrestrial ecosystems. Ecosystems 7, 563–572.

Erb, K.-H., Gingrich, S., Krausmann, F., Haberl, H., 2008. Industrialization, fossil fuels, and the transformation of land use. J. Ind. Ecol. 12:686–703. https://doi.org/10.1111/j.1530-9290.2008.00076.x.

Farrell, A.E., 2006. Ethanol can contribute to energy and environmental goals. Science 311:506–508. https://doi.org/10.1126/science.1121416.

Fernandes, S.D., Trautmann, N.M., Streets, D.G., Roden, C.A., Bond, T.C., 2007. Global biofuel use, 1850–2000. Glob. Biogeochem. Cycles 21. https://doi.org/10.1029/2006GB002836.

Fischer-Kowalski, M., Haberl, H., 2007. Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use. Edward Elgar Publishing.

Galán, E.S., Padró, R., Marco, I., Tello, E., Cunfer, G., Guzman, G.I., Gonzalez de Molina, M., Krausmann, F., Gingrich, S., Sacristán, V., Moreno, D., 2016. Widening the analysis of Energy Return On Investment (EROI) in agro-ecosystems: ocio-ecological transitions to industrialized farm systems (the Vallès County, Catalonia, c.1860 and 1999). Ecol. Model. 336:13–25. https://doi.org/10.1016/j.ecolmodel.2016.05.012.

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

Gingrich, S., Erb, K.-H., Krausmann, F., Gaube, V., Haberl, H., 2007. Long-term dynamics of terrestrial carbon stocks in Austria: a comprehensive assessment of the time period from 1830 to 2000. Reg. Environ. Chang. 7:37–47. https://doi.org/10.1007/s10113-007-0024-6.

Gingrich, S., Kušková, P., Steinberger, J.K., 2011. Long-term changes in CO_2 emissions in Austria and Czechoslovakia—identifying the drivers of environmental pressures. Energy Policy 39:535–543. https://doi.org/10.1016/j.enpol.2010.10.006.

Gingrich, S., Niedertscheider, M., Kastner, T., Haberl, H., Cosor, G., Krausmann, F., Kuemmerle, T., Müller, D., Reith-Musel, A., Jepsen, M.R., Vadineanu, A., Erb, K.-H., 2015. Exploring long-term trends in land use change and aboveground human appropriation of net primary production in nine European countries. Land Use Policy 47:426–438. https://doi.org/10.1016/j.landusepol.2015.04.027.

Gingrich, S., Lauk, C., Kastner, T., Krausmann, F., Haberl, H., Erb, K.-H., 2016. A forest transition: Austrian carbon budgets 1830–2010. In: Haberl, H., Fischer-Kowalski, M., Krausmann, F., Winiwarter, V. (Eds.), Social Ecology: Society-Nature Relations Across Time and Space. Springer International Publishing, pp. 417–431.

Gingrich, S., Marco, I., Aguilera, E., Padró, R., Cattaneo, C., Cunfer, G., Guzmán, G.I., MacFadyen, J., Watson, A., 2018a. Agroecosystem energy transitions in the old and new worlds: trajectories and determinants at the regional scale. Reg. Environ. Chang. 18:1089–1101. https://doi.org/10.1007/s10113-017-1261-y.

Gingrich, S., Theurl, M.C., Erb, K., Krausmann, F., 2018b. Regional specialization and market integration: agroecosystem energy transitions in Upper Austria. Reg. Environ. Chang. 18:937–950. https://doi.org/10.1007/s10113-017-1145-1.

Gonzalez de Molina, M., Toledo, V.M., 2014. The Social Metabolism. A Socio-Ecological Theory of Historical Change, Environmental History. Springer, New York.

Greimel, M., Handler, F., Blumauer, E., 2002. Abschlussbericht. Arbeitszeitbedarf in der österreichischen Landwirtschaft. Bundesanstalt für alpenländische Landwirtschaft Gumpenstein, Irdning.

Guzmán, G.I., González de Molina, M., Soto Fernández, D., Infante-Amate, J., Aguilera, E., 2018. Spanish agriculture from 1900 to 2008: a long-term perspective on agroecosystem energy from an agroecological approach. Reg. Environ. Chang. 18: 995–1008. https://doi.org/10.1007/s10113-017-1136-2.

Haberl, H., 1995. Menschliche Eingriffe in den natürlichen Energiefluß von Ökosystemen: Sozio-ökonomische Aneignung von Nettoprimärproduktion in den Bezirken Österreichs. Social Ecology Working Papers. IFF Social Ecology, Wien.

Haberl, H., Fischer-Kowalski, M., Krausmann, F., Weisz, H., Winiwarter, V., 2004. Progress towards sustainability? What the conceptual framework of material and energy flow accounting (MEFA) can offer. Land Use Policy 21:199–213. https://doi.org/10.1016/j.landusepol.2003.10.013.

Haberl, H., Winiwarter, V., Andersson, K., Ayres, R.U., Boone, C., Castillo, A., Cunfer, G., Fischer-Kowalski, M., Freudenburg, W.R., Furman, E., Kaufmann, R., Krausmann, F., Langthaler, E., Lotze-Campen, H., Mirtl, M., Redman, C., Reenberg, A., Wardell, A., Warr, B., Zechmeister, H., 2006. From LTER to LTSER: conceptualizing the socioeconomic dimension of long-term socioecological research. Ecol. Soc. 11.

Haberl, H., Erb, K.-H., Krausmann, F., 2014. Human appropriation of net primary production: patterns, trends, and planetary boundaries. Annu. Rev. Environ. Resour. 39: 363–391. https://doi.org/10.1146/annurev-environ-121912-094620.

Hall, C.A.S., 2011. Introduction to special issue on new studies in EROI (energy return on investment). Sustainability 3:1773–1777. https://doi.org/10.3390/su3101773.

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. https://doi.org/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. https://doi.org/10.1021/es052024h.

Handler, F., Stadler, M., Blumauer, E., 2006. Standardarbeitszeitbedarf in der österreichischen Landwirtschaft: Ergebnis der Berechnung der einzelbetrieblichen Standardarbeitszeiten. Research report/FJ-BLT - Francisco Josephinum Wieselburg, Biomass - Logistics - Technology. HBLFA Francisco Josephinum, Wieselburg.

Hanisch, E., 2002. Die Politik und die Landwirtschaft. In: Hanisch, E., Bruckmüller, E., Sandgruber, R., Weigl, N. (Eds.), Geschichte Der Österreichischen Land- Und Forstwirtschaft Im 20. Jahrhundert. Politik - Gesellschaft - Wirtschaft. Ueberreuter, Wien, pp. 15–190.

Harchaoui, S., Chatzimpiros, P., 2018. Energy, nitrogen, and farm surplus transitions in agriculture from historical data modeling. France, 1882–2013: energy, nitrogen, and farm surplus transitions. J. Ind. Ecol. online first. https://doi.org/10.1111/jiec.12760.

Hatirli, S.A., Ozkan, B., Fert, C., 2005. An econometric analysis of energy input–output in Turkish agriculture. Renew. Sust. Energ. Rev. 9:608–623. https://doi.org/10.1016/j.rser.2004.07.001.

Herridge, D.F., Peoples, M.B., Boddey, R.M., 2008. Global inputs of biological nitrogen fixation in agricultural systems. Plant Soil 311:1–18. https://doi.org/10.1007/s11104-008-9668-3.

Hitschmann, H.H., 1891. Vademecum für den Landwirth (M. Perles).

IPCC, 2014. Climate change 2014: synthesis report. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.

Jepsen, M.R., Kuemmerle, T., Müller, D., Erb, K., Verburg, P.H., Haberl, H., Vesterager, J.P., Andrič, M., Antrop, M., Austrheim, G., Björn, I., Bondeau, A., Bürgi, M., Bryson, J., Caspar, G., Cassar, L.F., Conrad, E., Chromý, P., Daugirdas, V., Van Eetvelde, V., Elena-Rosselló, R., Gimmi, U., Izakovicova, Z., Jančák, V., Jansson, U., Kladnik, D., Kozak, J., Konkoly-Gyuró, E., Krausmann, F., Mander, Ü., McDonagh, J., Pärn, J., Niedertscheider, M., Nikodemus, O., Ostapowicz, K., Pérez-Soba, M., Pinto-Correia, T., Ribokas, G., Rounsevell, M., Schistou, D., Schmit, C., Terkenli, T.S., Tretvik, A.M., Trzepacz, P., Vadineanu, A., Walz, A., Zhllima, E., Reenberg, A., 2015. Transitions in European land-management regimes between 1800 and 2010. Land Use Policy 49: 53–64. https://doi.org/10.1016/j.landusepol.2015.07.003.

Jeroch, H., Drochner, W., Simon, O., 2008. Ernährung landwirtschaftlicher Nutztiere: Ernährungsphysiologie, Futtermittelkunde, Fütterung. UTB.

Jones, M.R., 1989. Analysis of the use of energy in agriculture—approaches and problems. Agric. Syst. 29:339–355. https://doi.org/10.1016/0308-521X(89)90096-6.

Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S., 2012. Global changes in diets and the consequences for land requirements for food. Proc. Natl. Acad. Sci. 109:6868–6872. https://doi.org/10.1073/pnas.1117054109.

Katzmann, W., Schrom, H., Blau, P., Treytl, J.M., 1991. Umweltreport Österreich. Kremayr & Scheriau.

Kim, E., Arnoux, M., Chatzimpiros, P., 2018. Agri-food-energy system metabolism: a historical study for northern France, from nineteenth to twenty-first centuries. Reg. Environ. Chang. 18:1009–1019. https://doi.org/10.1007/s10113-017-1119-3.

Koning, N.B.J., Van Ittersum, M.K., Becx, G.A., Van Boekel, M.A.J.S., Brandenburg, W.A., Van Den Broek, J.A., Goudriaan, J., Van Hofwegen, G., Jongeneel, R.A., Schiere, J.B., Smies, M., 2008. Long-term global availability of food: continued abundance or new scarcity? NJAS - Wagening. J. Life Sci. 55:229–292. https://doi.org/10.1016/S1573-5214(08)80001-2.

Kränzlein, T., Mack, G., 2007. Analyse der Energieeffizienz der schweizerischen und österreichischen Landwirtschaft: ein regionalisierter Ansatz. In: Pöchtrager, S. (Ed.), Jahrbuch Der Österreichischen Gesellschaft Für Agrarökonomie, pp. 65–77.

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. https://doi.org/10.1016/S0264-8377(00)00042-9.

Krausmann, F., Haberl, H., 2002. The process of industrialization from the perspective of energetic metabolism. Ecol. Econ. 41:177–201. https://doi.org/10.1016/j.ecolecon.2012.02.019.

Krausmann, F., Haberl, H., 2007. Land-use change and socio-economic metabolism. A macro view of Austria 1830–2000. In: Fischer-Kowalski, M., Haberl, H. (Eds.), Socioecological Transitions and Global Change: Trajectories of Social Metabolism and Land Use. Edward Elgar, Cheltenham, UK, Northampton, USA, pp. 31–59.

Krausmann, F., Haberl, H., Schulz, N.B., Erb, K.-H., Darge, E., Gaube, V., 2003. Land-use change and socio-economic metabolism in Austria—part I: driving forces of land-use change: 1950–1995. Land Use Policy 20:1–20. https://doi.org/10.1016/S0264-8377(02)00048-0.

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

Krausmann, F., Erb, K.-H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.D., 2013. Global human appropriation of net primary production doubled in the 20th century. Proc. Natl. Acad. Sci. 110:10324–10329. doi https://doi.org/10.1073/pnas.1211349110.

Leach, G., 1976. Energy and Food Production. IPC Science and Technology Press, Guildford.

von Lorenz, J.R., 1866. Statistik der Bodenproduction von zwei Gebietsabschnitten Oberösterreichs (Umgebung von St. Florian und von Grünburg). k.k. Ministerium für Handel und Volkswirthschaft, Wien.

Marco, I., Padró, R., Cattaneo, C., Caravaca, J., Tello, E., 2018. From vineyards to feedlots: a fund-flow scanning of sociometabolic transition in the Vallès County (Catalonia) 1860–1956–1999. Reg. Environ. Chang. 18:981–993. https://doi.org/10.1007/s10113-017-1172-y.

Markussen, M., Østergård, H., 2013. Energy analysis of the Danish food production system: food-EROI and fossil fuel dependency. Energies 6:4170–4186. https://doi.org/10.3390/en6084170.

Mayrhofer, I., 2014. Die Anfänge der mineralischen Düngung in Österreich-Ungarn (1848–1914). Social Ecology Working Papers. IFF Social Ecology, Vienna.

Mohr, S.H., Wang, J., Ellem, G., Ward, J., Giurco, D., 2015. Projection of world fossil fuels by country. Fuel 141:120–135. https://doi.org/10.1016/j.fuel.2014.10.030.

Murphy, D.J., Hall, C.A.S., Dale, M., Cleveland, C., 2011. Order from chaos: a preliminary protocol for determining the EROI of fuels. Sustainability 3:1888–1907. https://doi.org/10.3390/su3101888.

Niedrist, G., Tasser, E., Lüth, C., Dalla Via, J., Tappeiner, U., 2009. Plant diversity declines with recent land use changes in European Alps. Plant Ecol. 202:195–210. https://doi.org/10.1007/s11258-008-9487-x.

Odum, H.T., 1973. Energy, ecology and economy. Ambio 6, 220–227.

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

Parcerisas, L., Dupras, J., 2018. From mixed-farming to intensive agriculture. Energy profiles of Quebec's agriculture between 1871 and 2011. Reg. Environ. Chang. 18: 1047–1057. https://doi.org/10.1007/s10113-018-1305-y.

Pellegrini, P., Fernández, R.J., 2018. Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution. Proc. Natl. Acad. Sci. 201717072. https://doi.org/10.1073/pnas.1717072115.

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

Pérez Neira, D., Soler Montiel, M., Delgado Cabeza, M., Reigada, A., 2018. Energy use and carbon footprint of the tomato production in heated multi-tunnel greenhouses in Almeria within an exporting agri-food system context. Sci. Total Environ. 628–629: 1627–1636. https://doi.org/10.1016/j.scitotenv.2018.02.127.

Pimentel, D., Patzek, T.W., 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Nat. Resour. Res. 14:65–76. https://doi.org/10.1007/s11053-005-4679-8.

Pimentel, D., Hurd, L.E., Bellotti, A.C., Forster, M.J., Oka, I.N., Sholes, O.D., Whitman, R.J., 1973. Food production and the energy crisis. Science 182:443–449. https://doi.org/10.1126/science.182.4111.443.

Pracha, A.S., Volk, T.A., 2011. An edible energy return on investment (EEROI) analysis of wheat and rice in Pakistan. Sustainability 3:2358–2391. https://doi.org/10.3390/su3122358.

Raworth, K., 2012. A safe and just space for humanity: can we live within the doughnut. Oxfam Policy Pract. Clim. Change Resil. 8, 1–26.

Riegler, J., 1988. Zukunft für die Bauern. Manifest für eine ökosoziale Agrarpolitik in Österreich (Wien).

Rougoor, C.W., Van Zeijts, H., Hofreither, M.F., Bäckman, S., 2001. Experiences with fertilizer taxes in Europe. J. Environ. Plan. Manag. 44:877–887. https://doi.org/10.1080/09640560120087615.

Schneider, F., Hofreither, M. (Eds.), 1988. Chance Landwirtschaft: Wege und Perspektiven für die neunziger Jahre. Agrarverlag, Wien.

Shafiee, S., Topal, E., 2009. When will fossil fuel reserves be diminished? Energy Policy 37: 181–189. https://doi.org/10.1016/j.enpol.2008.08.016.

Solomon, B.D., 2010. Biofuels and sustainability: biofuels and sustainability. Ann. N. Y. Acad. Sci. 1185:119–134. https://doi.org/10.1111/j.1749-6632.2009.05279.x.

Soto, D., Infante-Amate, J., Guzmán, G.I., Cid, A., Aguilera, E., García, R., González 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. https://doi.org/10.1016/j.ecolecon.2016.04.017.
Stanhill, G., 1974. Energy and agriculture: a national case study. Agro-Ecosystems 1, 205–217.
Steinberger, J.K., Krausmann, F., Eisenmenger, N., 2010. Global patterns of materials use: a socioeconomic and geophysical analysis. Ecol. Econ. 69:1148–1158. https://doi.org/10.1016/j.ecolecon.2009.12.009.
Steinhart, J.S., Steinhart, C.E., 1974. Energy use in the US food system. Science 184, 307–316.
Tello, E., Galán, E., Sacristán, V., Cunfer, G., Guzmán, G.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. https://doi.org/10.1016/j.ecolecon.2015.11.012.
Tollmann, A., 1991. Die Belastung des Grundwassers in Österreich Ursachen, Ausmaß, Folgen, Abhilfe. Mitteilungen Österr. Geol. Ges. 83, 125–150.