Regional Environmental Change (2018) 18:929–936
https://doi.org/10.1007/s10113-018-1322-x

EDITORIAL

Agroecosystem energy transitions: exploring the energy-land nexus in the course of industrialization

Simone Gingrich[1] · Geoff Cunfer[2] · Eduardo Aguilera[3,4]

Received: 5 March 2018 / Accepted: 11 March 2018 / Published online: 24 March 2018

Keywords EROI · Energy return on investment · Energy · Agroecosystems · Long-term socio-ecological research · LTSER

Why quantify energy throughputs in agroecosystems?

Agriculture and forestry are integral parts of the socio-economic energy system, not only in the recent context of biofuel production, but also from a fundamental, long-term socio-ecological perspective (Rappaport 1971; Bayliss-Smith 1982; Sieferle 2001). For most of human history, biomass was humanity's major source of primary energy, and since the Neolithic Revolution, agriculture and forest use have been society's main mechanism for harnessing energy. Even though fossil fuels and other modern energy forms became dominant in the last two centuries, biomass remains vital to the current energy regime (Krausmann et al. 2008). Humanity continues to rely on agriculture for food supply. Taken together, food and feed constitute the energy sources essential for the reproduction of human and livestock populations and the provision of human and animal labor (Kander et al. 2014). In the future, we will need to feed a growing population while also moving away from fossil energy and toward a new type of low-carbon energy system. Both goals will require an efficient and sustainable agricultural production system, one with high biomass output but which does not deplete soil fertility or depend on high inputs of non-renewable resources. Understanding the energy dynamics of agroecosystems is thus crucial to feeding the people of the world in the face of an uncertain energy future.

Industrialization had profound and long-term impacts on both societal and ecological processes far beyond agriculture. From a socio-ecological perspective, industrialization resulted from technological innovations enabling the mobilization of previously untapped fossil energy sources, conceptualized in the notion "energy transition" (Grübler 2008). The increasing technical energy availability fostered unprecedented economic growth (Ayres and Warr 2010) and the emergence of modern political structures (Mitchell 2009; Scheffer et al. 2017). The ecological impacts of industrialization were equally substantial and have led researchers to propose a new geological era, the "Anthropocene," in which, they argue, humans have become a global geological force (Crutzen 2006; Steffen et al. 2007). One important effect of industrialization was the partial separation of energy provision from land use: pre-industrial societies relied on local, land-based resources for their energy provision, e.g., fuelwood for cooking, heating, and manufacturing or draught animals, fed on biomass, for transport (Fernandes et al. 2007). Industrializing societies, on the other hand, supplemented their energy supplies with modern energy carriers (Pachauri and Jiang 2008) that require much less land for extraction or generation. Paradoxically, industrialization processes have usually resulted in increasing total biomass extraction and consumption, as has been demonstrated in long-term socio-ecological research (LTSER, see Haberl et al. 2006; Singh et al. 2013). Various case studies around the globe have studied increasing biomass extraction and use at different scales, ranging

✉ Simone Gingrich
simone.gingrich@boku.ac.at

Geoff Cunfer
geoff.cunfer@usask.ca

Eduardo Aguilera
emagufer@upo.es

[1] Institute of Social Ecology, University of Natural Resources and Life Sciences, Vienna, Austria

[2] Department of History, University of Saskatchewan, Saskatoon, Canada

[3] Agro-Ecosystems History Laboratory, Pablo de Olavide University, Seville, Spain

[4] Department of Animal Production, University of Córdoba, Córdoba, Spain

from regional (Cusso et al. 2006; Delgadillo-Vargas et al. 2016) to national (Kastner 2009; Gingrich et al. 2015b; de Souza and Malhi 2017) and global (Krausmann et al. 2013). However, relatively little is known about the changes in composition and quantity of energy use for biomass extraction, and changes in energy returns on investment.

This special issue addresses the changing energy processes in agroecosystems over the socio-ecological transition, including various types of energetic inputs and outputs, as well as energy fluxes within agroecosystems. It evaluates regional trajectories of agricultural and forestry intensification before, during, and after industrialization, with a particular focus on agroecosystem energetics and energy returns on investment. The diverse case studies presented here come from Europe and the Americas and address nearly two centuries of agricultural transformation. Table 1 shows that they represent various scales, continents, climates, and eras. Some places were deeply interconnected with global food markets throughout the study period while others were mainly subsistence-focused and embraced newly emerging trade connections in the course of industrialization. All of them changed dramatically in the study period, with rising energy outputs and inputs. We term this increase in energy throughput, resulting from the introduction of fossil energy carriers and the continuous internal energy circulation, an "agroecosystem energy transition". This introduction lays out the general methodological framework adopted in many of the papers of the special issue, and presents two major features of agroecosystem energy transitions.

A joint methodological framework

In order to evaluate the effects of industrialization on the energy-land nexus, methodological harmonization is necessary. Comparative research requires a certain degree of methodological consistency, especially when comparing quantitative evidence across both space and time. The existing literature about energy returns on investment (EROI) presents particular challenges of methodological harmonization (Murphy et al. 2011). As a ratio of outputs to inputs, EROI is doubly affected by any difference in accounting metrics or choice of system boundaries. In complex contexts like agroecosystems, the choice of system boundaries for energy accounting is particularly difficult (Giampietro et al. 1992) and with only a few exceptions (Conforti and Giampietro 1997; Arizpe et al. 2011), case study comparisons are impossible.

Working together in an international research project, many of the authors of the articles in this special issue agreed on general accounting principles that allow methodological harmonization. The result is a consistent and comparable analysis of agroecosystem energy transitions in Europe and the Americas across many different geographical settings and through nearly two centuries. Nine of the 12 contributions to this special issue adopt a consistent accounting procedure, recently developed by the research team (Galán et al. 2016; Tello et al. 2016; Guzmán and González de Molina 2017). The aim of this methodological framework is to analyze agroecosystem energetics throughout the industrialization process, capturing potential shifts from local biomass transfers to external energy inputs. Eight of the empirical articles present case studies in Europe (Fraňková and Cattaneo 2018; Gingrich et al. 2018b; Guzmán et al. 2018; Marco et al. 2018) and the Americas (Cunfer et al. 2018; Infante-Amate and Picado 2018; MacFadyen and Watson 2018; Parcerisas and Dupras 2018), and one is a comparative analysis of regional trajectories (Gingrich et al. 2018a). Both the methods development and empirical analyses were made possible by a long-term collaboration of the research team.

Table 1 Content of the special issue: basic features of case study regions and methodological approach

	Case study	Time period	Spatial scale	Climate	Method consistent with other papers
Fraňková and Cattaneo 2018	Holubi Zhor	1840–2011	Farm	Temperate	Yes
MacFadyen and Watson 2018	Prince Edward Island, Canada	1880–1996	Farm, regional	Oceanic temperate	Yes
Macro et al. 2018	Vallés County, Catalonia, Spain	1860–1999	Regional	Mediterranean	Yes
Gingrich et al. 2018b	St Florian, Grünburg, Austria	1830–2000	Regional	Temperate	Yes
Cunfer et al. 2018	Nemaha, Chase, Decatur, USA	1880–1997	Regional	Semi-arid	Yes
Parcerisas and Dupras 2018	Quebec, Canada	1871–2011	Regional	Humid continental	Yes
Marull et al. 2018	Cauca river valley, Colombia	1943–2010	Regional	Tropical	No
Kim et al. 2018	Seine River Basin, France	1860–2010	Regional	Oceanic temperate	No
Gingrich et al. 2018a	Comparative	1830–2000	Regional—comparative	Diverse	Yes
Infante-Amate and Picado 2018	Coffee in Costa Rica	1935–2010	Crop scale (national)	Tropical	Yes
Guzmán et al. 2018	Spain	1900–2008	National	Mostly mediterranean	Yes
Henriques and Warde 2018	Denmark, UK	1870–1914	National	Oceanic temperate	No

Understanding farmers' decisions about energy management means confronting the internal energy loops in farm systems. If it is to allow analysis of long-term farm management and important transitions, then an agroecosystem energy model must be able to specify key energy carriers and converters using available historical sources. The model presented here balances the complexity necessary to reveal internal energy loops against the challenge of reconstructing energy processes from historical documents.

The model (Fig. 1) defines five functional subsystems, which can be merged into two larger subsystems. The human beneficiaries of agricultural production are represented by the local farming community and the rest of society. The farming community comprises all farm households in a village, a manorial estate, a plantation, or an agroindustrial enterprise, depending on the social context. The members of the farming community typically live within or near the agroecosystem, they continuously make decisions about land management, and they are the ones performing land-related labor. In subsistence societies, they constitute all of the consumers of farm produce. In many places and times, however, some portion of the grain, meat, firewood, and other produce flows out to the rest of Society. Depending on place and time, this flow may take the form of in-kind rents or tithes, trade goods exchanged with nearby urban centers, or exports to global commodities markets.

The agroecosystem, for its part, appears as three subsystems, each representing the major energy components of farms. At the center is farmland, including all of the cropland, pasture, and woodland managed by the farming community. Many farm communities manage complex energy and nutrient transfers across these landscape types in order to sustain farm production over the long term (Guzmán et al. 2011; Tello et al. 2012; Gingrich et al. 2015a).

Livestock are essential in many farm systems. They are energy converters, changing chemical energy into mechanical energy, high-quality food energy, and manure. They can make non-arable land productive and convert grass and crop residues, biomass unsuitable for human nutrition, into food. But they can also feed on high-quality crop products like corn or oats, competing with people for food. The energy services livestock provide and the type of biomass they consume vary greatly across farming systems. The Livestock-Barnyard

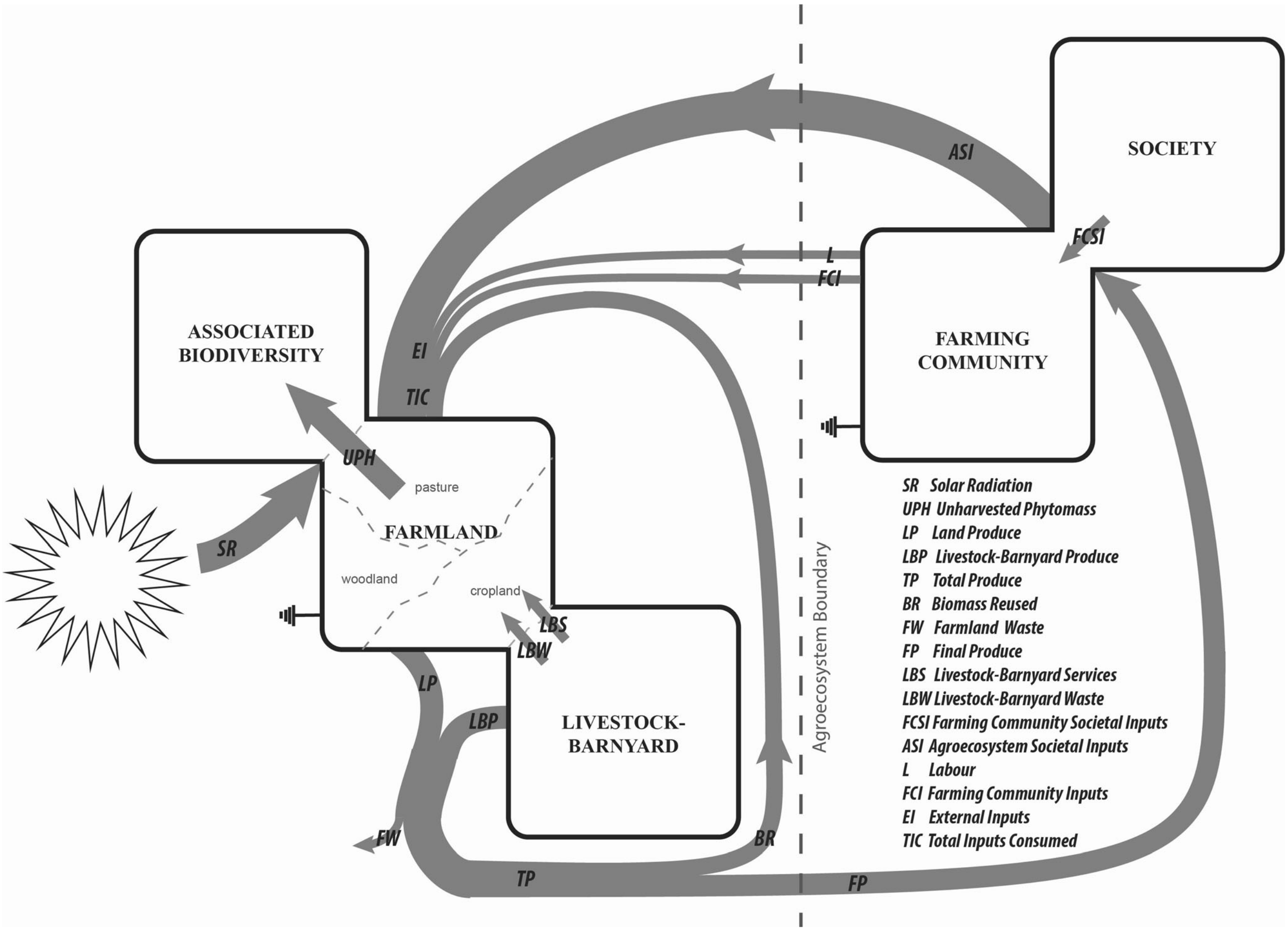

Fig. 1 An energy model of agroecosystems, optimized for estimation based on historical sources (adopted from Tello et al. 2015)

subsystem is responsible for a great deal of the complexity in and diversity across agroecosystems.

Finally, farmers also indirectly support ecosystem processes that they do not directly manage, including important ecosystem services that are valuable or even essential to the survival and prosperity of human communities (Liu et al. 2007; Guzmán and González de Molina 2015). Agroecosystem properties like soil fertility and water and air quality depend on species only indirectly managed by farmers, e.g., by deliberately leaving spaces uncultivated or fallow. The corresponding agroecosystem compartment is termed associated biodiversity in our model.

The five subsystems are linked to one another by energy flows. Land produce (LP) represents the energy contained in harvested plant matter taken from cropland, pasture, and woodland, including crop production, harvested residues, pasture grass grazed by livestock, and wood. Livestock-barnyard produce (LBP) accounts for the energy contained in products from domesticated animals, including milk, wool, and meat, as well as live animals exported to market.

A portion of land produce cycles back into the local farm system as biomass reused (BR) while the remainder, final produce (FP), is available for human consumption, either in the local farming community or by the rest of society. Biomass reused remains within the agroecosystem, redirected to keep the system operating. Typically, the largest part of biomass reused goes to feed livestock. Biomass reused, as Fig. 1 makes clear, has a dual existence: it is drawn from the farm's produce, but is also an input into the agroecosystem. Biomass reused thus brings the model around to the input side of the equation. Total inputs consumed (TIC) aggregates all of the energy flows coming into the agroecosystem, including internal biomass reused and external inputs (EI). From the local farming community external inputs include human labor (L) and farming community inputs (FCI). Labor is the physical energy exerted by the agriculturally active population. The size of the energy input from human labor is usually remarkably small, often an order of magnitude lower than the other energy flows in the system. Labor productivity is a useful indicator for evaluating farm energetics and can be derived from this model when all relevant energy flows are specified (Cunfer and Krausmann 2009). Another relatively small energy flow is FCI, the organic wastes from households returned to farmland or to livestock-barnyard, such as kitchen waste fed to hogs or, in some instances, human waste composted for cropland fertilizer.

Agroecosystem societal inputs (ASI) represents all energy imported from outside the local farm system. In traditional agriculture, ASI was typically small, perhaps livestock feed imported to meet a local shortfall. Under the fossil fuel energy regime, ASI includes the energy embodied in purchased tractors, trucks, and implements; the fuel to power them; electricity; imported feed for livestock; and, often the largest component, the energy embodied in synthetic fertilizers and other agrochemicals. Livestock-barnyard services (LBS) are energy flows from the livestock-barnyard subsystem to farmland, such as draft power and manure, which are not part of livestock-barnyard produce contributing to total produce. They are not counted as part of total inputs consumed because the feed energy for those livestock is already included with biomass reused, and adding these flows would constitute double-counting.

Unharvested phytomass (UPH) finally is the part of net primary production which is not directly exploited by people that therefore remains available to associated biodiversity. Often ignored in energy analyses of agriculture because it carries no economic value, these energy flows are nonetheless crucial for the long-term sustainability of agroecosystems. Unharvested phytomass includes such energy flows as unharvested weeds, grain lost to birds and pests, stubble decomposed by soil microorganisms, or the NPP generated in hedgerows.

Several measures of energetic efficiency can be derived from this model, dividing different types of produce by different types of energy inputs. The most relevant indicators or energy returns on investment (EROI) used in many of the case studies in this special issue include final EROI (FEROI), internal final EROI (IFEROI), and external final EROI (EFEROI), defined in the equations below:

$$\mathrm{EFEROI} = \frac{\mathrm{FP}}{\mathrm{EI}} \tag{1}$$

$$\mathrm{IFEROI} = \frac{\mathrm{FP}}{\mathrm{BR}} \tag{2}$$

$$\mathrm{FEROI} = \frac{\mathrm{FP}}{\mathrm{TIC}} = \frac{\mathrm{FP}}{(\mathrm{EI}+\mathrm{BR})} \tag{3}$$

EFEROI (Eq. 1) is the most similar to traditional EROI measures in agroecosystems, representing the ratio of final produce to external inputs. IFEROI (Eq. 2), conversely, is the ratio of final produce to biomass reused. FEROI (Eq. 3) is the ratio of final produce to total inputs consumed, i.e., the sum of external inputs and biomass reused. The framework allows for identifying different intensification trajectories, depending on the relative amount of external versus internal energy inputs to agroecosystems (Tello et al. 2016).

Despite sharing the same general energy model, agroecosystem boundary, and basic concepts described above, the case studies presented in this special issue do not allow a model to overcome common sense. A certain degree of methodological divergence remains among the case studies, due to differences in source availability, research questions, and environmental context. Not all studies used the same level of disaggregation, or assessed all energy flows proposed in the model. In addition, slight variations of accounting and estimation procedures remain, which in part also impact the results. For example, depending on local land management practices, some analyses consider leaves dropped by trees as biomass reused (Infante-Amate and Picado 2018) or grain stubble left standing in the field as unharvested phytomass (Cunfer et al. 2018;

MacFadyen and Watson 2018) in contrast to the other articles. The extent of farmland sometimes includes total area in a census reporting unit (Cunfer et al. 2018; MacFadyen and Watson 2018) and sometimes only the agriculturally defined area (Gingrich et al. 2018b) and some cases accounted fodder exported to other regions as biomass reused (Guzmán et al. 2018) while others treated it as final produce (Gingrich et al. 2018b). Finally, different approaches were chosen to address energy flows through the livestock system in different ways (Gingrich et al. 2018b; Marull et al. 2018). With the common methodological framework and the minor remaining methodological differences, we believe this special issue to be as close to methodological harmonization as possible with case studies diverging in scale, scope, and time. We are therefore able to draw some very general conclusions on agroecosystem energy transitions.

General features of agroecosystem energy transitions

External inputs added to, but did not replace local biomass reused

A major finding that results from the empirical studies presented in this special issue is that the introduction of fossil fuel-based external inputs into agroecosystems did not reduce internal flows of biomass reused or unharvested phytomass in many of the case studies presented, and in fact often increased them. An initial hypothesis was that pre-industrial agroecological intensification relied on increasing biomass reused and labor to raise final produce, while agricultural industrialization allowed imported external inputs to replace local biomass reused. This hypothesis was based on insights from Vallés County, Catalonia, Spain, which experienced a very particular trajectory of industrialization (Marco et al. 2018; Galán et al. 2016; Tello et al. 2016). Traditional fertilizing techniques involved the labor-intensive burial of biomass in the soil (“formiguers”). By the end of the twentieth century, agriculture in this region was dominated by intensive swine feedlots that were virtually independent of the local land. Here, biomass reused was almost entirely replaced by external inputs in the form of feed imported from the Americas.

The other case studies reported in this special issue reveal that the massive replacement of internal energy flows by external ones was not the general rule. Industrialization did increase external inputs everywhere, but biomass reused remained stable or even grew in many case studies. In some of the case studies, there was a slight decline of local (or domestic) feed and fodder production providing for livestock, either because livestock density went down (Fraňková and Cattaneo 2018), or because fodder was increasingly imported from other regions, as in Sankt Florian, Austria (Gingrich et al. 2018b) and in Prince Edward Island, Canada (MacFadyen and Watson 2018). Even at the national scale, this replacement is evident, as in Spain (Guzmán et al. 2018), a country specializing in livestock production using large quantities of imported fodder. More common than an actual replacement of local feed supply was an increase in fodder imports and stable biomass reused for feed. This occurred in cattle-rearing regions like Decatur and Chase, Kansas, USA (Cunfer et al. 2018), in Grünburg, Austria (Gingrich et al. 2018b), and in Quebec, Canada (Parcerisas and Dupras 2018).

The national-scale energetic impacts of exporting livestock products based on domestic feed and fodder production are displayed for the case of Denmark (Henriques and Warde 2018), and the case of France demonstrates the increasing interconnectedness of food production and the processing industries (Kim et al. 2018).

The focus on agroecosystem energetics adopted in this special issue, studying societal energy inputs and local biomass circulation processes contrasts previous analyses of energy use in agroecosystems and food systems (Pimentel and Pimentel 1996; Smil 2000) and adds an important dimension: fossil energy-based inputs to agroecosystems did not merely replace agricultural labor or biotic fertilizing techniques. Instead, industrialization led to stable or even increasing biomass recirculation within many agroecosystems, in particular in the context of (partly) locally fed livestock production.

The composition of final produce determines energy returns on investment across space, time, and scales

The method employed in many of the case studies in this special issue operates at the agroecosystem level, thus conflating energy fluxes of crop production, livestock production and forestry. While comparable analyses have been carried out (usually for shorter time periods) at national levels (Steinhart and Steinhart 1974; Cleveland 1995; Hatirli et al. 2005), this has rarely been done at the regional scale, or in a comparative way across more than two cases (Arizpe et al. 2011; Hamilton et al. 2013). The results presented here reveal that both the energy profile of regional agroecosystems, and their temporal dynamics, are highly dependent on a specialization in one of three production foci: cropping, forestry, and livestock rearing.

Contrary to expectations based on previous comparative work within Austria (Gingrich et al. 2013), energy profiles did not diverge from “more similar” in the nineteenth century to “more diverse” in the late twentieth century. However, the determinants of specialization changed. While biophysical framework conditions (population density, climate) explain some differences quite well in the nineteenth century, this direct link loosened in the course of industrialization (Gingrich et al. 2018a). In particular, the concentration of import-based feedlots only loosely connects to specific biogeographic conditions. Given the increase of regional specialization in the course of agricultural industrialization, at least in European agroecosystems, the fact that IFEROI values in our case studies did not diverge through time came as a surprise. Of course, the sample of case studies in this special issue is modest, and more research is required to determine whether this observation holds true more generally.

The size of the case studies was not a major explanatory variable for energy profiles either. That finding is also surprising, given that the distinction between internal versus external energy inputs depends on the size of the case study. At the farm scale in Holubi Zhor, Czech Republic, IFEROI in 2012 was 3.4, higher than the national-level IFEROI of Spain, which was 0.72 in 2008 (Fraňková and Cattaneo 2018; Guzmán et al. 2018). This would confirm the general idea that ceteris paribus, a larger agroecosystem relies on more internal inputs per unit of final produce than a smaller one. However, differences among regional-scale IFEROI values were equally great, both in preindustrial and industrialized agroecosystems, and across sizes. In a consistent comparison, IFEROI values among various case studies differed by a factor of about five in both the late 19th and the late twentieth century (Gingrich et al. 2018a).

At the same time, trade and transportation systems had a great impact on energy profiles, both in the past and the present. Regions accessible through ocean or riverine shipping, such as Denmark (Henriques and Warde 2018), Catalonia, Spain (Marco et al. 2018), and Northern France (Kim et al. 2018), or through early railway lines, like the U.S. Great Plains (Cunfer et al. 2018), were able to produce agricultural products for international markets and, as in the USA, import fertilizers and fossil fuels already in the nineteenth century. According to the results in this special issue, supraregional market relations impacted the energy profiles of local subsistence agriculture already in the nineteenth century in many places of the world. Trade and transport of biomass products and production factors was not an entirely new phenomenon that appeared with industrialization.

Differences in energy returns of investment both among regions and through time were linked more to the specialization of agroecosystem management than to the size of the region or the time point of analysis. For example, a focus on wood extraction led to higher EROIs (both IFEROI and EFEROI), because wood requires comparatively little labor or machinery for extraction, and provides high amounts of energy, albeit for fuel or material use only, not for food consumption. As with all other land management practices, forestry was heavily mechanized during the twentieth century, but compared to other practices of land use, EROIs on woodlands remained rather stable, as demonstrated by the Canadian case studies in Prince Edward Island, where wood extraction dominated agroecosystem management (MacFadyen and Watson 2018). The degree of forest exploitation made a huge difference in Vallés, Catalonia, Spain, where there was significant reforestation during industrialization but with no impact on EROIs, because wood resources are not presently extracted (Marco et al. 2018).

Final produce from cropland saw the most change over time in terms of per-area productivity, and also in terms of energy inputs. Final produce from cropland increased by factors of two to four per unit of cropland area in the case studies investigated. At the same time, inputs to cropland changed from mostly manual labor, livestock traction, and manure to machinery, fuel, and mineral fertilizers. While industrialized farmers no longer applied animal draught power to cropland, they continued to spread manure in many of the case studies. Regions focusing on cropland saw remarkable increases in per-area productivity over time (Gingrich et al. 2018b; Marull et al. 2018), and some displayed recent increases in IFEROI and FEROI values.

Livestock management, on the other hand, is the least energy-efficient process in land management. During every time period, the relative contribution of livestock products to final produce decreased FEROI values. Livestock systems diverged over time, with locally fed livestock retaining a surprising presence throughout industrialization in these case studies, resulting in stable IFEROI values.

Understanding the relevance of different specialization trajectories in regional and global contexts, and systematically identifying different types of specialization trajectories according to their energetics (e.g., among different livestock management regimes), will be tasks for future research.

Concluding remarks

The case studies presented in this special issue of Regional Environmental Change display the diversity of agricultural land management across many different landscapes, climates, cultural and economic contexts, and time periods. They reveal the central role of energy in agroecosystems and the deep interconnections between rural hinterlands and urban markets for farm produce. And they outline several pathways of agroecosystem energy transitions over the past two centuries. A rigorous and uniform application of energy accounting principles makes a truly comparative sustainability analysis possible, enabling us to draw two rather general conclusions based on the selection of case studies presented here: (1) external energy inputs added to, but did not replace local biomass reuses in the course of industrialization and (2) the composition of final produce determined energy returns on Investment across space, time, and scales. The methodological model adopted here provides a basis for future studies in other places and times and with other particular research questions in mind. It will continue to enable learning about past agroecosystem energy transitions, and drawing lessons for future sustainable agriculture.

Acknowledgements Open access funding provided by University of Natural Resources and Life Sciences Vienna (BOKU). The authors thank the contributors to the special issue for their diligent work and patience, the editors of Regional Environmental Change Wolfgang Cramer, Gabriele Götz, and Christopher Reyer for their continuous support in handling the manuscripts, as well as all collaborators on the linked projects "Sustainable Farm Systems: Long-Term Socio-Ecological Metabolism in Western Agriculture" (Canada's Social Sciences and Humanities Research Council Partnership Grant 895-2011-1020) and "Sustainable Farm Systems and Transitions in Agricultural Metabolism" (Spain's Science Ministry grant HAR2012-38920-C02-02).

References

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

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

Bayliss-Smith TP (1982) Ecology of agricultural systems. Cambridge University Press, Cambridge

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

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

Crutzen PJ (2006) The Anthropocene. In: Ehlers E, Krafft T (eds) Earth system science in the Anthropocene. Springer, Berlin, pp 13–18

Cunfer G, Krausmann F (2009) Sustaining soil fertility. Agricultural practice in the old and new worlds. Glob Environ 4:9–43. https://doi.org/10.3197/ge.2009.020402

Cunfer G, Watson A, MacFadyen J (2018) Energy profiles of an agricultural frontier: the American Great Plains, 1860–2000. Reg Environ Change this issue. https://doi.org/10.1007/s10113-017-1157-x

Cusso 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. https://doi.org/10.1016/j.ecolecon.2005.05.026

de Souza P, Malhi Y (2017) Land use change in India (1700-2000) as examined through the lens of human appropriation of net primary productivity: land-use change in India. J Ind Ecol https://doi.org/10.1111/jiec.12650

Delgadillo-Vargas O, Garcia-Ruiz R, Forero-Álvarez J (2016) Fertilising techniques and nutrient balances in the agriculture industrialization transition: the case of sugarcane in the Cauca river valley (Colombia), 1943–2010. Agric Ecosyst Environ 218:150–162. https://doi.org/10.1016/j.agee.2015.11.003

Fernandes SD, Trautmann NM, Streets DG, Roden CA, Bond TC (2007) Global biofuel use, 1850–2000. Glob Biogeochem Cycles 21: https://doi.org/10.1029/2006GB002836

Fraňková E, Cattaneo C (2018) Organic farming in the past and today: sociometabolic perspective on a Central European case study. Reg Environ Change this issue. https://doi.org/10.1007/s10113-016-1099-8

Galán ES, Padró R, Marco I, Tello E, Cunfer C, Guzmán GI, González de Molina M, Krausmann F, Gingrich S, Sacristán V, Moreno-Delago 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. 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, Schmid M, Gradwohl M, Krausmann F (2013) How material and energy flows change socio-natural arrangements: the transformation of agriculture in the eisenwurzen region, 1860–2000. In: Singh SJ, Haberl H, Chertow M, Mirtl M, Schmid M (eds) Long term socio-ecological research. Studies in society-nature interactions across spatial and temporal scales. Springer, Cham, pp 297–313

Gingrich S, Haidvogl G, Krausmann F, Preis S, Garcia-Ruiz R (2015a) Providing food while sustaining soil fertility in two pre-industrial alpine agroecosystems. Hum Ecol 43:395–410. https://doi.org/10.1007/s10745-015-9754-0

Gingrich S, Niedertscheider M, Kastner T, Haberl H, Cosor G, Krausmann F, Kuemmerle T, Müller D, Reith-Musel A, Jepsen MR, Vadineanu A, Erb K-H (2015b) 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, Marco I, Aguilera E, Padró R, Cattaneo C, Cunfer G, Guzmán GI, MacFadyen J, Watson A (2018a) Agroecosystem energy transitions in the old and new worlds: trajectories and determinants at the regional scale. Reg Environ Change this issue https://doi.org/10.1007/s10113-017-1261-y

Gingrich S, Theurl MC, Erb K, Krausmann F (2018b) Regional specialization and market integration: agroecosystem energy transitions in Upper Austria. Reg Environ Change this issue. https://doi.org/10.1007/s10113-017-1145-1

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

Guzmán GI, González de Molina M (2015) Energy efficiency in agrarian systems from an agroecological perspective. Agroecol Sustain Food Syst 39:924–952. https://doi.org/10.1080/21683565.2015.1053587

Guzmán GI, González de Molina M (eds) (2017) Energy in agroecosystems: a tool for assessing sustainability. CRC Press, Taylor & Francis Group, Boca Raton

Guzmán GI, Gonzalez de Molina M, Alonso AM (2011) The land cost of agrarian sustainability. An assessment. Land Use Policy 28:825–835. https://doi.org/10.1016/j.landusepol.2011.01.010

Guzmán GI, 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 Change this issue. https://doi.org/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 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(2):13 [online]. http://www.ecologyandsociety.org/vol11/iss2/art13/

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

Hatirli SA, 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

Henriques ST, Warde P (2018) Fuelling the English breakfast: hidden energy flows in the Anglo-Danish trade 1870-1913. Reg Environ Change this issue. https://doi.org/10.1007/s10113-017-1166-9

Infante-Amate J, Picado W (2018) Energy flows in the coffee plantations of Costa Rica: from traditional to modern systems (1935–2010). Reg Environ Change this issue. https://doi.org/10.1007/s10113-017-1263-9

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

Kastner T (2009) Trajectories in human domination of ecosystems: human appropriation of net primary production in the Philippines during the 20th century. Ecol Econ 69:260–269. https://doi.org/10.1016/j.ecolecon.2009.08.019

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 Change this issue. https://doi.org/10.1007/s10113-017-1119-3

Krausmann F, Schandl H, Sieferle RP (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 TD (2013) Global human appropriation of net primary production doubled in the 20th century. Proc Natl Acad Sci 110:10324–10329. https://doi.org/10.1073/pnas.1211349110

Liu J, Dietz T, Carpenter SR, Alberti M, Folke C, Moran E, Pell AN, Deadman P, Kratz T, Lubchenco J, Ostrom E, Ouyang Z, Provencher W, Redman CL, Schneider SH, Taylor WW (2007) Complexity of coupled human and natural systems. Science 317:1513–1516. https://doi.org/10.1126/science.1144004

MacFadyen J, Watson A (2018) Energy in a woodland-livestock agroecosystem: Prince Edward Island, Canada, 1870–2010. Reg Environ Change. https://doi.org/10.1007/s10113-018-1315-9

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 Change this issue. doi: https://doi.org/10.1007/s10113-017-1172-y

Marull J, Delgadillo O, Cattaneo C, La Rota MJ, Krausmann F (2018) Socioecological transition in the Cauca river valley, Colombia (1943–2010): towards an energy-landscape integrated analysis. Reg Environ Change this issue. https://doi.org/10.1007/s10113-017-1128-2

Mitchell T (2009) Carbon democracy. Econ Soc 38:399–432. https://doi.org/10.1080/03085140903020598

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. https://doi.org/10.3390/su3101888

Pachauri S, Jiang L (2008) The household energy transition in India and China. Energy Policy 36:4022–4035. https://doi.org/10.1016/j.enpol.2008.06.016

Parcerisas L, Dupras J (2018) From mixed-farming to intensive agriculture. Energy profiles of Quebec's agriculture between 1871 and 2011. Reg Environ Change this issue. doi: https://doi.org/10.1007/s10113-018-1305-y

Pimentel D, Pimentel M (1996) Food, energy and society. University Press of Colorado, Niwot

Rappaport RA (1971) The flow of energy in an agricultural society. Sci Am 225:117–133. https://doi.org/10.1038/scientificamerican0971-116

Scheffer M, van Bavel B, van de Leemput IA, van Nes EH (2017) Inequality in nature and society. Proc Natl Acad Sci 114:13154–13157. https://doi.org/10.1073/pnas.1706412114

Sieferle RP (2001) The subterranean forest: energy systems and the industrial revolution. White Horse Press, Cambridge

Singh SJ, Haberl H, Chertow MR, Mirtl M, Schmid M (eds) (2013) Long term socio-ecological research: studies in society-nature interactions across spatial and temporal scales. Springer, Dordrecht

Smil V (2000) Feeding the world. A challenge for the twenty-first century. MIT Press, Cambridge

Steffen W, Crutzen PJ, McNeill JR (2007) The Anthropocene: are humans now overwhelming the great forces of nature? Ambio 36:614–621. https://doi.org/10.2307/25547826

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

Tello E, Garrabou R, Cussó X, Olarieta JR, Galán E (2012) Fertilizing methods and nutrient balance at the end of traditional organic agriculture in the Mediterranean bioregion: Catalonia (Spain) in the 1860s. Hum Ecol 40:369–383. https://doi.org/10.1007/s10745-012-9485-4

Tello E, Galán ES, Cunfer G, Guzmán G, González de Molina M, Krausmann F, Gingrich S, Sacristán V, Marco I, Padró R, Moreno-Delgado D (2015) A proposal for a workable analysis of Energy Return On Investment (EROI) in agroecosystems. Part I: Analytical approach. Social Ecology Working Paper 156. Vienna

Tello E, Galán E, Sacristán V, Cunfer G, Guzmán GI, 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