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Research Report

Energy input and food output: The energy imbalance across regional agrifood systems

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Abstract

Biomass was the principal energy source in preindustrial societies; their agriculture provided more energy than it required. Thus, the energy return on energy investment (EROEI) needed to be >1. Recent studies have indicated that this may not be the case for modern industrialized agrifood systems (AFSs). Although the green revolution radically improved agricultural yields, it came at the expense of increased energy inputs, mainly in the form of fossil fuels. AFSs relying on external energy pose a food security risk, an economic issue for agricultural producers, and an environmental issue for all. Previous EROEI studies investigated mainly certain groups of commodities, typically at the local or national level. Here, a comprehensive global analysis shows that current AFSs have a lower EROEI than previously estimated. Globally, EROEI has increased from 0.68 in 1995 to 0.91 in 2019. In low-income regions, AFSs are still energy sources, but their EROEI has declined with increasing wealth, reflecting the growing utilization of fossil fuels. AFSs of high-income regions are energy sinks, although their EROEI has improved. Food processing is responsible for 40% of the total energy use in the global AFS, notably larger than fertilizer, which accounts for 17%. More than half of the energy use in food processing is for livestock products that also require disproportionate energy input through their inefficient conversion of (human-edible) feed. Livestock products use 60% of energy inputs while delivering <20% of food calories.

Keywords: EROI, footprint, food system, agroecosystem, net energy analysis

Significance Statement

A global model of energy use in agriculture and food production was built to examine the ratio of food calorie outputs to energy carrier inputs, the energy return on energy investment (EROEI). A ratio of >1 signifies that the agrifood system (AFS) is an energy source, as all preindustrial systems needed to be because agriculture and forestry were the sources of energy. A ratio of <1, observed in mid- and high-income regions, indicates an AFS dependent on external energy inputs, commonly fossil fuels. Reducing the energy demand of AFSs is essential to reduce food security risk, ensure social and economic sustainability for agricultural producers, and reduce environmental impacts.

Introduction

The role of energy in agrifood systems

Food has always been an essential energy source for human subsistence. However, agrifood systems (AFSs) have become dependent on external energy inputs (EEIs) since the green revolution of the second half of the 20th century. These EEIs are used both directly and indirectly in AFS to produce, apply, and operate chemical fertilizers, pesticides, machinery, storage, cooling, transport, processing, and large-scale farming and food production facilities (1). On the one hand, the green revolution enabled countries to reduce hunger while growing their population and the rest of the economy (2). On the other hand, the energy dependency means that human subsistence becomes dependent on external energy, which for the food system primarily is in the form of fossil fuels (3).

An AFS reliant on EEIs would not be problematic, if energy was abundant and easily accessible and came without any environmental costs. Though, this is the case neither for fossil nor for renewable energy sources. The former is abundant but often structurally scarce and has severe environmental consequences, while the latter might be abundant in theory and environmentally friendlier, but it is not easily accessible whenever it is needed. Thus, such reliance turns the question of food security into a question of energy security (4).

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The consequences of such reliance were already apparent during the oil crisis of the 1970s. During the crisis, both food and energy prices soared due to the former's dependency on the latter (5): a dependency which has only grown alongside subsidies to the agricultural industry (6). Subsidies allowed the agricultural industry to rely on unsustainable (energy) inputs (7). The AFSs have since only increased its energy dependency through further industrialization. More recent geopolitical events such as the 2007 financial crisis, the Arab Spring, and most notably the Russo-Ukrainian War have had a severe impact on food availability and prices, largely due to the AFS dependency on EEIs (8). These risks are most pronounced in highly industrialized AFS, which are primarily found in high-income countries. However, lower-income countries that rely on food import or aid from highly industrialized AFS can be severely affected due to their lack of financial capacity to deal with the price shock (4).

Internationalization of the global economy through the last decades means that food products, as well as their EEIs, are increasingly traded globally. Consequently, environmental impacts associated with the production and use of food and EEIs are also global (9, 10). The scope and scale of the environmental impacts of AFS are severe and well documented (9, 11, 12). Many detrimental environmental impacts are enabled by the high use of EEIs, primarily in the form of fossil fuels.

The ongoing climate change and biodiversity crises are severely impacting AFS, as they increase the AFS' vulnerability to extreme weather and biotic stresses (13). Agricultural producers are also facing social and economic challenges due to their high reliance on EEIs, which exposes them to changes in availability and prices of these inputs (14). Reducing AFS reliance on EEIs has been identified as a key lever for social sustainability in the systems (4, 15).

Understanding how AFSs rely on EEIs is thus essential for their environmental and social sustainability and to guarantee food security. AFSs produce a large variation of food products, which differ significantly in their energy, macronutrient, and micronutrient contents. Although the latter two are vital for human health, the former is the primary need of humans and provides the simplest basis for cross-comparison of foods. Hence, to compare AFS across time, space, and food products, this study sets out to investigate the energy output of AFS in relation to EEIs required to sustain it. In other words, we conduct a net energy analysis of AFS by considering their EROEI, which tells us whether systems constitute an energy source or sink (16). More specifically, the EROEI is the ratio between the calorie content of food consumed by humans and the energy required to produce it in the AFS, both directly and indirectly through its supply chain.

Our model

Our model is made by coupling the environmentally extended multiregional input–output model EXIOBASE to the physical multiregional input–output model FABIO (17, 18). We use the hypothetical extraction method on EXIOBASE to calculate both the direct and indirect energy use (i.e. energy footprint) of the agricultural and food processing sectors (19). This includes fuels, electricity, heat, machinery production, transport services, etc. in all upstream sectors used to produce human food and feed for animals that are later consumed as food. The energy footprint of each sector is allocated to the respective FABIO commodities using their biomass weight shares. FABIO is then used to allocate the energy footprint from producer to the final consumer through a standard Leontief footprint calculation. Hence, all energy used in the supply chain of a food item is allocated to the country in which it is consumed, irrespective of which countries may be involved in the supply chain (see Materials and methods section for more details).

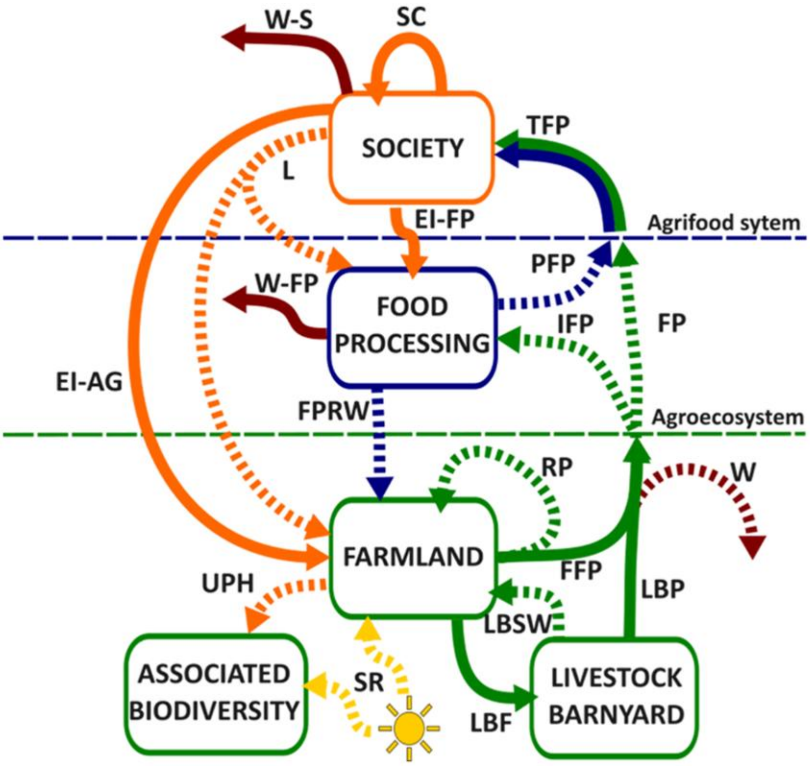
It is estimated that 70% of all energy use in AFS occurs beyond the farm gate (15). A large share of this is captured by including the food processing stage, but the energy used in distribution, wholesale, retail, storage, as well as food preparation (either at home or out at restaurants and similar) is not included in the model. Although some of the omitted sectors are available in EXIOBASE, the model does not distinguish between food and other commodities in these sectors. Disaggregating these sectors and their energy use by each type of food product is not possible with the current models nor with any other globally consistent dataset. Therefore, for the remainder of this paper, the term agrifood sector only includes agricultural and food processing sectors, while the rest of the supply chain stages are a part of the rest of society (see Figure 1). The implications of excluding these stages are considered in the discussion.

Food lost is not included as an output in the main EOREI calculation. The rationale for excluding lost food is that it reenters the system as an energy input into AFS through combustion or fermentation to biogas. Due to data limitations, our model is unable to differentiate between bio-based energy inputs made from food waste or other biomass sources. Reused biomass within the agrifood sector (e.g. food processing loss used as feed or other) is accounted for but does not enter the EROEI calculation as it is an internal flow. Hence, the output of the EROEI calculation only includes the human-edible calories made available to consumers. (Note: In Table 1 row 4, we do include food loss as an output in the EROEI calculation to investigate its effect on the EROEI of the global AFS. In SI 7, the energy output of food losses and food for other uses are reported.)

Contribution of this study

No strict convention exists on how a net energy analysis of AFS should be undertaken. Studies are conducted to answer various research questions and hence use different methods, system boundaries, and definitions of energy flows. Consequently, these differences need to be considered when comparing results (20–22). Efforts have been made within agroecology to create a net energy analysis framework for agroecosystems (20, 23–25). The framework has, however, only been applied to a few case studies that investigate specific farms or subnational agricultural regions in Western Europe and Northern America (26–33). Recently, the framework was applied to the global agroecosystem, but only at the aggregated system level (34). Prior studies with a national scope focused on a few key commodities, not allowing for interregional comparison (5, 6, 35–38). One existing study provides an interregional comparison, but considers its results "mostly tentative, since they rely on aggregated data, aggregated conversion factors, and simple statistical tools" (39). Furthermore, the study provides no details on the commodities analyzed. Apart from two global studies (34, 40) and four national studies on the Japanese (41), Chinese (42), Iranian (43), or Turkish (44) AFS, all recent EROEI studies are on either European or Northern American AFS (see supplementary information). The AFSs most of the world population rely on have only been considered in aggregated global studies.

Our study adopts the agroecosystem framework and extends it by including the food processing stage of the supply chain. Furthermore, it complements previous studies by using a globally consistent model with a significantly higher regional and food product resolution. As a result, it provides insights into regions



Label	Description
EI-AG	External inputs agriculture
EI-FP	External inputs food processing
FFP	Farmland final produce
FP	Final produce
FPRW	Food processing reused waste
IFP	Intermediate final produce
L	Labor
LBF	Livestock-barnyard feed
LBP	Livestock-barnyard final produce
LBSW	Livestock-barnyard services and reused waste
PFP	Processed final produce
RP	Reused final produce
SC	Supply chain
SR	Solar radiation
TFP	Total final produce
UPH	Unharvested phytomass
W	Waste farmland & livestock barnyard
W-FP	Losses and other uses in food processing
W-S	Losses and other uses in society

Fig. 1. System diagram showing the main flows in the AFS. Dashed lines represent flows that are not modeled explicitly in the model. In the system, EROEI is given by the ratio (**TFP** − (W-S + W-FP))/(EI-AG + EI-FP). See Section 5.2 in SI for more details on the individual flows. The solid output flows from society (external inputs into the AFS excluding labor) are calculated using EXIOBASE, while the solid output flows from agroecosystem components and the TFP flow are calculated using FABIO. Forestry is not considered in the system.

and products which have not been explicitly studied in a comparable manner before. The model is used to investigate how the EROEI differs across these products and/or regions and how it has changed through time as countries have changed their income level. The results and analysis are aggregated from 123 agricultural commodities to 10 food product groups and from 189 regions to 20 world regions and focus primarily on the change in the systems between the two 5-year periods, 1995–1999 and 2015–2019.

Results

Global changes and regional variations

The average EROEI of the global AFS increased from 0.68 to 0.91 from 1995 to 2019 (see Figure 2), a number that hides a lot of variation. In 2019, for every human-edible calorie provided to society, 10% (=1/0.91) more energy was needed to produce it. The EROEI ratio grew steadily over the years but appeared to have plateaued after peaking at 0.94 in 2014. The energy output of the AFS increased by 62% from 1995 to 2019, around twice the rate of the EROEI. EEIs grew 21% in the period, indicating an improved AFS energy efficiency. Agroecosystems have four main factors of production, namely capital, land, labor, and energy. Capital can be utilized to partially substitute both labor (e.g. tractor-driven plows) and land (e.g. feedlots) at the cost of increased EEIs. Hence, the development of these three factors may reveal systematic changes in the agroecosystem. Capital and agricultural land use grew steadily throughout the whole period, while agricultural labor peaked in 2003 and steadily decreased since. In 2019, the size of the labor force was 11% smaller than that in 1995. Net capital stock of agriculture almost doubled from 1995 to 2019, implying an increasing industrialization of the global agroecosystem (45). Additionally, agricultural land use grew only 28%, half the rate of energy output, indicating significantly improving yields and/or conversions efficiencies. However, shifts in demography and diets may also be factors that caused the apparent improving yields. The demand for crops with higher energy output per unit of land may be increasing due to faster population growth in low-income countries where products with low energy output per unit of land are luxury goods.

On a regional level, EROEIs range from 0.47 in Western Asia to 2.70 in Western Africa for the period 2015–2019 (see Figure 3). Of the world's population, 68% live in regions with EROEI >1, either in Africa (Western, Central, and Eastern Africa) or in Asia (Eastern, Southern, and Southeastern Asia) (see Figure 4, top panel). However, while the three African regions have EROEIs above 2.55, the three Asian regions have EROEIs ranging from 1.09 to 1.36 (see Diets and energy footprints section for more details).

In Figure 3, the EROEI is plotted against the GDP per capita (of the food consuming region) for the 20 regions at two time periods, namely 1995–1999 and 2015–2019. It shows the relation between increased income of a region and the external energy dependency of the food they consume. The plot indicates a V-shape, meaning that a percentage change in EROEI is negatively correlated with a percentage increase in GDP per capita up until a certain point. Beyond that point, the correlation flips, and EROEI is positively correlated with GDP per capita. The inflection point appears to be around 4,000–5,000 US dollars (USD) per capita (in 2015 prices). There are, however, three notable outliers. First, Southeastern Asia's EROEI has increased (by 4%) and not decreased as one

Table 1. Breakdown of the major flows in the global AFS and its changes from 1995–1999 to 2015–2019.

Variable/flows	Average in 2015–2019	Rel. change 1995–1999 to 2015–2019	Share in 2015–2019
Energy return on energy investment			
EROEI (excluding LBF, losses, and other uses)	0.91	+31%	
EROEI including LBF[a]	0.63	+25%	
EROEI including LBF but excluding fodder crops and grazing	0.75	+25%	
EROEI including losses in output	1.03	+38%	
EROEI including losses and LBF	0.72	+31%	
Energy input (EJ)			
Total (TEI = EI−AG + EI−FP + SC)	44.4	+15%	
Biofuels	3.4	+47%	8%
Renewable and nuclear	3.0	−3%	7%
Fossil fuels[b]	38.0	+14%	85%
Energy input—Agriculture (EJ)			
Agroecosystem excluding fertilizer[c] (EI-AG_{other})	19.0	+13%	43% (of TEI)
Direct[d] excluding fertilizer (EI-AG_{other} excluding SC)	3.8	−4%	20%
Electricity and heat (EI-AG_{other} and SC)	6.3	+19%	33%
Road transport[e] (EI-AG_{other} and SC)	4.6	+23%	25%
Other (EI-AG_{other} and SC)	4.2	+13%	22%
Fertilizer (EI-$AG_{fertilizer}$)	7.6	+11%	17% (of TEI)
Energy input—food processing (EJ)			
Total (EI-FP)	17.8	+17%	40% (of TEI)
Direct (EI-FP excluding SC)	2.9	+15%	16%
Electricity and heat (EI-FP and SC)	6.4	−6%	36%
Road transport (EI-FP and SC)	2.6	+85%	15%
Other (EI-FP and SC)	6.0	+34%	33%
Energy input—livestock-barnyard feed (EJ)			
Livestock-barnyard feed (LBF)	19.6	+35%	31% (of TEI + LBF)
LBF: Human edible	9.5	+54%	48%
LBF: Fodder crops	1.5	−4%	8%
LBF: Grazing	8.5	+27%	44%
Energy output			
Total (TFP, excluding W-FP and W-S)	40.4	+50%	
Farmland final produce (FFP)	33.6	+46%	83%
Livestock-barnyard final produce (LBP)	6.8	+73%	17%
Total (TFP, including W-FP and W-S)	45.9	+ 58%	
Losses and other uses (W−FP + W−S)	5.5	+168%	12%
Other			
Land use (Gha)	3.2	+23%	
Cropland	1.5	+19%	47%
Grazing	1.7	+26%	53%
Net capital (trillion USD in 2015 prices)	5.7	+77%	
Employment in agriculture (Mill.)	857	−12%	
Synthetic fertilizer input[f] (Mt)	124	+29%	

Plots showing the energy input shares by energy source type (i.e. biofuels, renewables and nuclear, or fossil fuels) and by flow (i.e. electricity and heat, road transport, direct energy use, fertilizer, and other) for each of the 20 regions are provided in the supplementary information (SI 1).
[a]LBF is included as an energy input.
[b]Assuming all energy input to fertilizer production is fossil.
[c]Synthetic fertilizer.
[d]Direct energy includes only energy products (fuels) used in the AFS directly and not direct use of electricity and heat.
[e]Road transport includes all road transport done by the agrifood sectors, as well as all upstream sectors. It does not include transport to retail stores or households.
[f]Numbers are lower than the total fertilizer use reported by FAOSTAT as we only consider the food consumed and due to adjustments made in the model (see Section 5.7.3 in SI 1).

would expect, despite its GDP having just passed 4,000 USD per capita. It remains above 1. Second, as Western Asia has on the contrary gone from 7,000 to 10,000 USD per capita, its EROEI declined by 13%. Although it is only a small drop in absolute terms (0.07), it contrasts with all other middle-income regions (4,000–10,000 USD per capita), whose EROEI increased. Lastly, the ROW region (Melanesia, Micronesia, Polynesia, and other island states) has as the only region decreasing GDP per capita while also decreasing the EROEI. The change in EROEI was, however, only around 1%, while the drop in GDP per capita was 5%.

The largest relative growth in EROEI from 1995 to 2019 was observed in four of the five high-income regions (excluding Australia and New Zealand) and Eastern Europe. These five regions all have grown their EROEIs by more than 70% from 1995–1999 to 2015–2019, although they did so from a level noticeably lower than all the other regions, starting around 0.3. That the other regions have not reached the same level of inefficiency (i.e. low EROEIs) before increasing their EROEIs (see Figure 3) suggests that agrifood methods, technology, and knowledge may be shared across regions. Hence, lower-income regions may not have to follow the trajectories of the high-income regions if they can adopt modern technologies directly. Central America and Southern Africa have both seen a 0.27-point increase in EROEI or 40 and 53%, respectively.

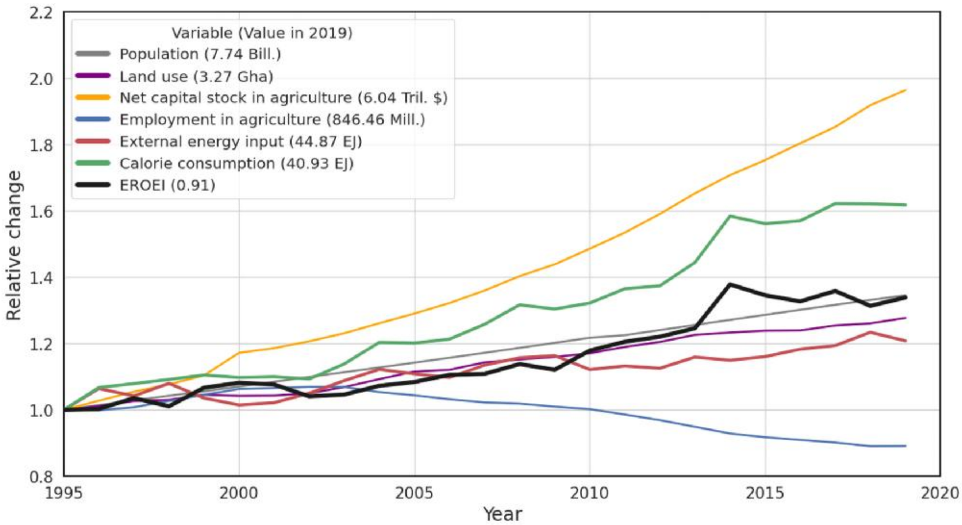


Fig. 2. Time series showing the relative development of the global AFS. *Employment* and *net capital stock in agriculture* (in trillion USD, 2015 prices) are based on FAOSTAT data, while the *population* (in billion capita) is based on the UN SNA Main Aggregates. The *external energy input* and human *calorie consumption* (both in exajoules) and *EROEI* (in exajoule of human calories consumed per exajoule of external energy input) have been derived in this paper. Data gaps for some countries are present in the data for *employment* and *net capital stock in agriculture*.

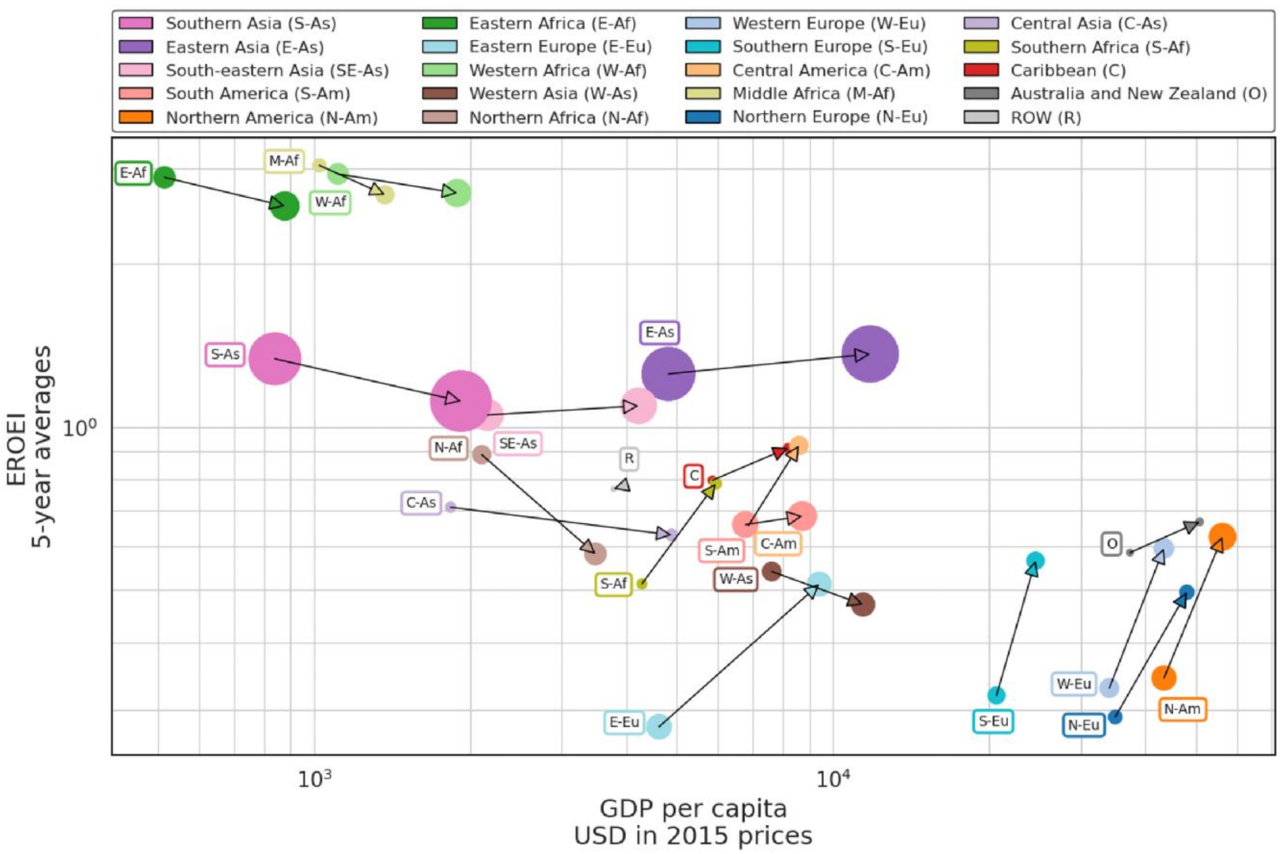


Fig. 3. The 5-year average EROEI plotted against GDP per capita. The arrow indicates the shift from 1995–1999 to 2015–2019, while the size of the points represents the population size.

The largest absolute reductions in EROEI from 1995 to 2019 were observed in four of the five African regions (excluding Southern Africa) and Southern Asia. While Northern, Eastern, and Middle Africa saw a 0.31–0.36-point drop in EROEI, Western Africa and Southern Asia saw a drop of 0.23 and 0.22 points, respectively. These are also the five regions with the highest population growth in the period, besides ROW and Western Asia. Northern Africa differs from the other regions as it has a

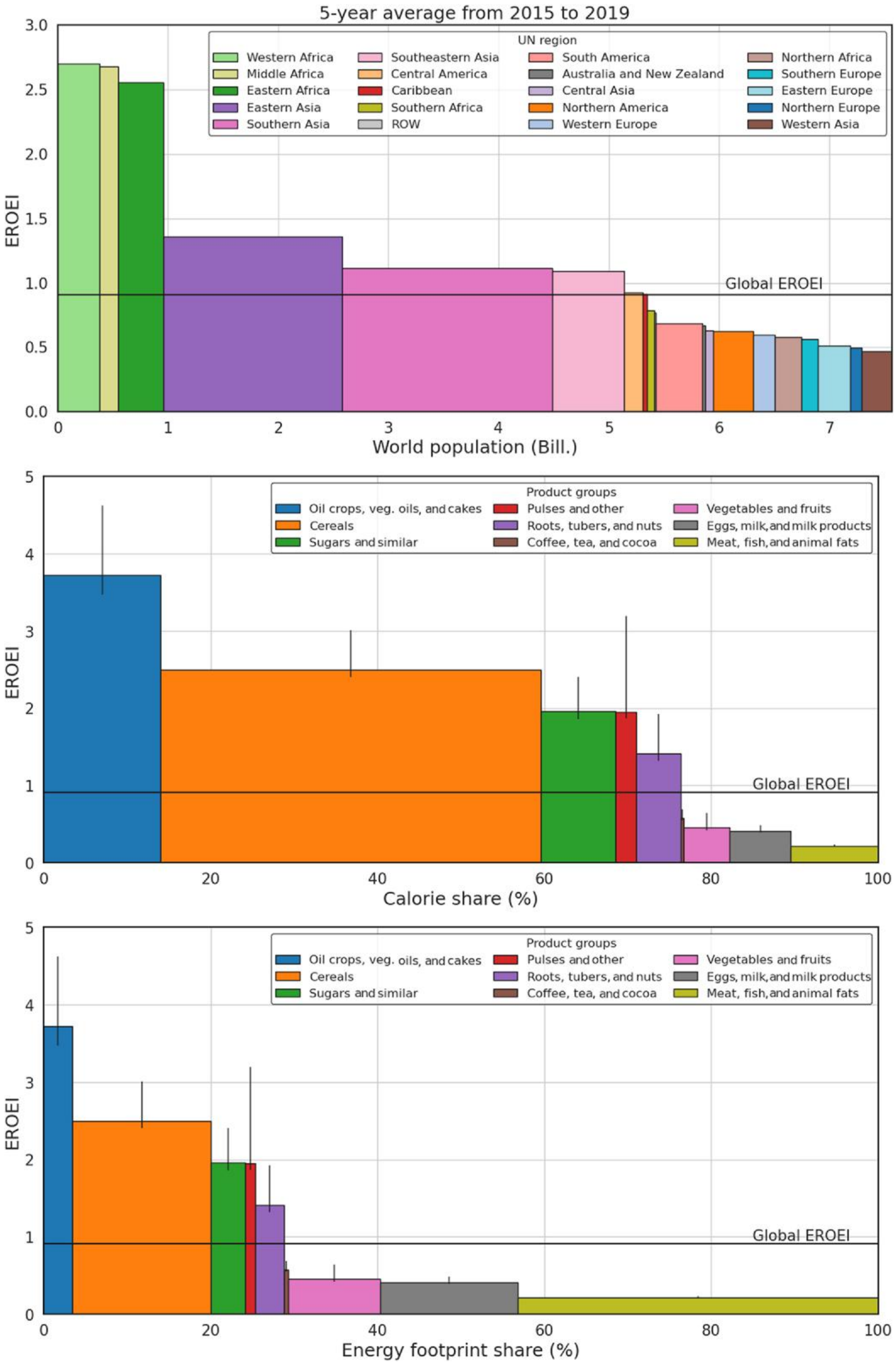


Fig. 4. The 5-year average EROEI for different UN regions (top panel), and product groups (bottom two panels) in the period 2015–2019. Width of bars show population, calorie shares, or energy footprint shares. Error bars on the commodity group represent the regional variation but shrunk with a factor of 10, i.e. a 0.5 on the positive error bar says there is a region whose EROEI ratio for that product group is 5 points higher than the global average for that product group. Regional versions of the two bottom panels are provided in supplementary information (Fig. S3 in SI 1) for all 20 regions. In addition, *energy input shares* plotted against *calorie shares* for each product group are also provided in the supplementary information (Fig. S1 in SI 1).

significantly larger GDP per capita. Central Asia has seen the largest growth in GDP per capita of all the regions (+63%) but has yet to reach an inflection point, although other regions have reached theirs at lower GDP per capita levels.

Table 1 shows a further breakdown of the energy flows in the global AFS in the period 2015–2019. Nonrenewables (fossil fuels) are the primary energy sources for AFS, making up roughly 85% of the total EEI. Bio-based fuels and other renewables only made up 8 and 7%, respectively. The three EEI flows, energy inputs into agriculture as fertilizer and other ($EI\text{-}AG_{fertilizer}$ or $EI\text{-}AG_{other}$), and energy inputs into food processing (EI-FP), make up 43, 17, and 40% of the total energy inputs, respectively (see Figure 1 for definitions and Table 1 for details on numbers). These have grown by 11–17% between 1995–1999 and 2015–2019. The growth rates across regions do vary, with high EROEI regions having the highest increase in energy use. Changes in shares for the EEI flows do not differ much across regions. One notable observation is that the five regions with the highest EROEI (Western, Middle, and Eastern Africa and Eastern and Southern Asia) have slightly lower EI-FP shares than the other regions. Regions such as Australia and New Zealand and Southern Africa have similar shares of energy from $EI\text{-}AG_{other}$ and EI-FP.

Diets and energy footprints

The largest share of the world's calories is consumed in the form of "Cereals" (see Figure 4, middle panel). Its share has, however, decreased by almost 7 percentage points from 1995–1999 to 2015–2019, where it now only accounts for around 46% of the total. Consequently, the share of all other product groups has increased. Most notably, the shares for "Oil crops, veg. oils, and cakes" have increased by 2.4 percentage points to 14% and "Eggs, milk, and milk products" increased by 1.4 percentage points to 7% of the calorie share. While the former product has the highest EROEI of all product groups (3.73), the latter has one of the lowest (0.41). In comparison, "Cereals" had in 2015–2019 an EROEI of 2.50. The shift to an increased share of "Oil crops, veg. oils, and cakes" in the global diet partially explains the increase in global EROEI. This may seem positive from an energetic perspective but have negative health consequences as the overconsumption of oil products is associated with increased health risk (46).

In 2015–2019, "Cereals" are the main source of calories for almost all regions, apart from Australia and New Zealand. For these countries, the two livestock product groups ("Meat, fish, and animal fats" and "Eggs, milk, and milk products") and "Sugars and similar" make up 20–21% of the diet each, and "Cereals" only make up only 20%. Other high-income regions are also characterized by their high shares of calories coming from livestock products. The three African regions with the highest EROEI all have some of the lowest consumption shares of "Sugars and similar," but a significantly higher share of "Roots, tubers, and nuts." High consumption shares of "Sugars and similar" are seen in most mid- and high-income regions. The diet of Western Asia, which has the lowest EROEI score, does not seem to differ significantly from regions with significantly higher EROEI scores such as Central America. Hence, they must be consuming food from less energy-efficient supply chains. Although the diets have changed for each region, there is no apparent pattern that can be related to the regions EROEI scores or GDP per capita.

The three African regions (Eastern, Middle, and Western Africa) and three Asian regions (Eastern, Southeastern, and Southern Asia) that have EROEI ratios >1 in 2015–2019 and make up most of the world population have in common that a large portion of their diet consisted of cereals. The difference between them, however, lies in the share of livestock products (<7% for the African regions and >11% for the Asian regions) and "Roots, tubers, and nuts" in their diet (>10% for the African regions and <5% for the Asian regions) in their diet (see SI 3 for a more detailed breakdown of the numbers).

The EROEIs of the same product group differ significantly from one region to another in 2015–2019 (see "error bars" in Figure 4, middle and bottom panels). For "Oil crops, veg. oils, and cakes" they vary from 1.2 in ROW to 12.6 in Western Africa and for "Cereals" from 1.6 in Southern Asia to 7.6 in Eastern Asia. Western Asia has in general some of the lowest EROEI scores across all product groups, which may explain its low overall EROEI. The EROEIs of livestock products vary significantly less than those of other product groups in absolute terms. In relative terms, livestock products also have some of the lowest variations (30–43%), while "Pulses and others," "Roots, tubers, and nuts," and "Vegetables and fruits" have the highest (72–76%).

Livestock products were responsible for almost 60% of the energy footprint of the global AFS but provided only 18% of the calories consumed in 2015–2019 (see Figure 4, bottom panel). In all regions, livestock products were responsible for more than 40% of the energy footprint (see SI 1 and SI 3 for regional plots and data, respectively). Southern Asia is an exception, where livestock products only used 34% of energy and "Cereals" needed more than 40%. Southern Asia had the lowest consumed calorie share from "Meat, fish, and animal fats" in their diet (2%), which could partially explain the low livestock share. Eastern, Middle, Northern, and Western Africa all have low shares of "Meat, fish, and animal fats" in their diet (3–5%) but have a high share of the energy footprint going to "Meat, fish, and animal fats" (>35%). Detailed numbers are given in SI 3, while Figure S3 in SI 1 provide regional versions of Figure 4.

In the five high-income regions and some middle-income regions (Eastern and Southeastern Asia, South America, Central Asia, and Eastern Europe), the livestock product energy footprint share was in the range of 63–73% for the period 2015–2019. For the rest of the regions, the share is below 60% and around 45% for Western and Eastern Africa. In lower EROEI regions, "Eggs, milk, and milk products" tend to make up a larger share in the energy footprint, while in high EROEI regions (except Eastern and Southeastern Asia) "Cereals" and "Roots, tubers, and nuts" are more dominant. Western Asia has an unusually high share of energy going into "Vegetables and fruits" at 21%. Northern Africa, Southern Europe, and Caribbean have shares of 17, 15, and 14%, respectively, for "Vegetables and fruits," while it is 11% or less for all other regions. Like the diets, the shares of energy footprint by product groups have changed for each region, but there is no clear pattern related to the regions EROEI scores or GDP per capita.

The energy content of livestock-barnyard feed (LBF) is not included as an EEI to the system, although the energy used to produce the feed is included. This includes the energy footprint of oil crops meals/cakes as these are explicitly traced in the model, but not the energy footprint distillers grains and other by-products. In some studies, LBF is included in the EROEI as a natural energy input flow. However, in our case LBF is an intermediate flow in the agroecosystem and therefore excluded in the EROEI calculation (see Table 1 for EROEI ratios with LBF included). Nonetheless, the flow reveals the potential in shifting to a nonlivestock-based diet. In 2015–2019, the global livestock-barnyard sector turned 19.6 EJ of primary crops and calories from grazing into 6.8 EJ of livestock product. Almost half of the 19.6 EJ were human-edible crops (9.5 EJ), while the rest were from grazing (8.6 EJ) and fodder crops (1.5 EJ) (see Table 1). Assuming the input-to-output ratio to be independent of the type of feed, then livestock product calorie made from nonhuman-edible crops is 3.5 EJ ($=10.1/19.6 \times 6.8$ EJ). Though, this is likely an overestimate, as grain-fed cattle has been shown to produce up to 32% more meat than grass-fed cattle California (47). Though, whether grain-feeding provides the same increase in meat production for other cattle breeds or livestock animals globally is unclear. If human-edible crops used as feed were to be consumed directly by humans, the same primary production system would be able to produce 13 EJ (=9.5 EJ + 3.5 EJ) of human-edible calories, which is a 91% (=13/6.8−1) increase in energy output.

Discussion

Limited scope and comparison with previous work

The United Nations Food and Agriculture Organization (FAO) divides the supply chain of food into eight stages that all require energy: (i) production of inputs, (ii) production of raw crops and livestock products, (iii) transport from farm to food processing, (iv) temporary storage and handling, (v) food processing, (vi) transport and distribution to wholesale and retail, (vii) marketing and distribution, and (viii) purchase, transport, and consumption by end-user (48). In our study, only the first five stages are included due to the lack of detailed data on these stages. The results from other studies may provide an indication for the importance of the later stages.

The FAO estimates only 30% of the energy demand of AFS occur before the farm gate, i.e. stages 1 and 2 (15). In our system, stages 1 and 2 account for 60% of the total EEI ($EI\text{-}AG_{other} + EI{-}AG_{fertilizer}$). Assuming that the shares reported by the FAO remain the same until 2019, then our model, which includes stages 1 to 5, captures only 50% (=30%/60%) of the total energy demand. For stages 1 to 5, our model allocates 7.5% (=44.4 EJ/582 EJ) of the global net energy use. If we are to scale this up assuming that stages 6 to 8 require the same amount of energy as stages 1 to 5, the full supply chain would be responsible for 15% of the total global energy demand. This is only half what the FAO estimates (15). The numbers provided by the FAO, however, come with a caveat that they are only indicative and should be interpreted with care (49).

Nevertheless, stages 6 to 8 are clearly important and including these could potentially half the global EROEI. The energy footprint of stages 6 to 8 is highly region, product, and meal specific (48). Most livestock products, fruits, and vegetables require cooling during transport and storage (stages 6 and 7), while most cereals and legumes do not. Contrary, fruits and vegetables do not necessarily require cooking, while livestock products, roots, legumes, and cereals do (stage 8).

A recent study found that road transport makes up 20% of the total food system greenhouse gas emissions (50), although this has been disputed (51). In our study, road transport makes up almost 17% of the total EEIs (excluding fertilizer), although we do not distinguish between the transport of food or other goods used in the upstream supply chain. According to our model, stages 1 to 5 were responsible for 8.2% of total road transport energy use (directly and indirectly through its supply chain) in the years 2015–2019.

Three previous EROEI studies have included household energy use for food storage and preparation. They estimate that it is responsible for 18 to 32% of agrifood system energy use (52–54). However, different system boundaries make these results non-comparable to ours results. Moreover, they only consider three specific regions, namely Spain, Canada, and United States. Life cycle inventory databases could potentially be used to derive indications of the potential size of the latter stages but cannot deliver the same reliability as statistical data or inform about regional differences or changes over time. The FAO estimates that the energy footprint share for stages 6 and 7 are higher in high-income regions, while that for stage 8 is higher in low-income regions (48).

In terms of eating at a restaurant or cooking at home, a previous study found that environmental impacts (including fossil fuel use) of a specific Spanish dish were typically higher when consumed at restaurants (55). These results should not be generalized to other dishes consumed at restaurants in other countries.

Energy required to sustain human labor in the food supply chain is not counted as an input, which would otherwise reduce the EROEI of AFS. Currently, there is no dataset that provides labor information for food products along the full supply chain. Previous studies have shown that human and animal labor inputs to agriculture have remained stable over the last few decades at around 10 EJ on a global level (34) but have decreased for high-income regions on longer timescale (20). Human labor in agriculture is more prevalent in less industrialized AFS, while food processing employs more people in industrialized AFS in high-income countries (56).

In a supplementary table (see Table in SI 5), we compare EROEI ratios calculated using our model with those reported by 23 previous studies (23, 26–28, 30–32, 34, 37, 38, 40–44, 52, 53, 57–62). The table builds on a recent review (34). To make our model results comparable to these studies, crude adjustments are made to our system boundaries, though crucial differences persist in system boundaries, methodology, and definition of energy flows. On a global level, our results, when adjusted, are directly comparable to those of two other global studies (34, 40). One of these studies differs in two ways. First, they include forestry in their system boundary, and second, they use final energy use for external input (as opposed to net energy use in our model, see Section 5.3 in SI for further information). These two differences may explain their higher EROEI values (34). The other study considers only crops and reports an EROEI within the ranges reported by our model (40). In general, our model predicts lower EROEI values than all other previous studies, which is expected given our wider system boundary. When the system boundary of our model is adjusted, the EROEI ratios are similar to previous studies. However, there are four exceptions, which report lower EROEI ratios than our model. Two of these studies focus on subnational regions with high livestock production share, while the other two use primary energy flows for their external inputs. Using primary energy use, which is larger than net energy use, will reduce their EROEI.

Food security, impacts, and challenges

Our results show AFSs differ significantly across world regions. Findings from previous studies, for European or North America, are therefore not applicable to the food system of the rest of the world. Differences prevail in EROEI scores, diets, and EEIs, as well as their EROEI vs GDP per capita trajectories.

AFSs in Europe and Northern America resemble one another in terms of EROEI, as well as the structure of energy footprints and diets. Contrary, previous studies reported varying EROEI ratios for these regions and even for subnational regions in some countries (see Table in S5). The move from subsistence to commercial agriculture and international trade contribute to the convergence of EROEIs (see Figure 3). The more industrialized a food system is, the more EEIs are needed in its supply chain (replacing manual labor), which will be reflected in the EROEI for the different regions. International trade (63) means that regions with inefficient production will increasingly import feed and foodstuff they cannot produce competitively.

In understanding the energy dependence of our food system, it is crucial to include both energy use beyond the farm gate and further upstream in supply chains, as these account for a large portion of the total energy footprint. Our results show that food processing accounts for 40% of the total energy use in the AFS, while fertilizer energy is responsible for around 17%. The latter is notably lower than what initial studies in the field had estimated (1, 5).

While calorie consumption increased 50% from 1995–1999 to 2015–2019, fertilizer use has increased by 29% and its energy footprint only by 11%. This indicates significant improvements in both fertilizer production and use efficiencies, the latter potentially through improved seeds. Meanwhile, direct energy use at the farm level has decreased 4%, signaling improved efficiencies (e.g. better equipment). However, this has all come at the expense of more indirect energy use further upstream in the supply chains. An example is the use of more automated barn systems, which require less manual labor and might improve output, but require more energy both to be produced, maintained, and operated. To fully account for the energy demand of the agroecosystem, it is therefore important to adopt a supply chain perspective, especially as supply chains are getting longer (64).

In 2019, the global net energy use was 582 EJ. According to our model, 44.4 EJ (7.5%) was used directly or indirectly by AFS to provide 40.4 EJ of food. This high energy use raises the question of whether it makes sense for our societies to spend so much energy on something which in theory should be an energy source for human society. The freeing of the global labor force from agricultural work has allowed our societies to prosper. However, if labor wages increase at a higher rate than energy prices, the economic incentive to increase the EROEI may be reduced, as EEIs have been shown to substitute labor due to changes in relative prices (65). Improved energy efficiencies will increase EROEI, but there are physical limits to such improvements, and other solutions will be needed.

An increased energy use that is primarily fossil fuel based (and will likely remain so for a few decades) raises a dilemma for many countries, the dilemma of mitigating climate change while also satisfying their citizens' demand for food. Although both may be essential for the survival of their populations, only the latter has immediate and direct consequences. The question is whether it is sensible that almost 60% of our EEIs into AFS go to producing livestock products that only meet 18% of our calorie demand (see Figure 4). A livestock production is subsidized in most high-income regions, which skews consumption away from more sustainable alternatives (66–68). Natural grazing systems could potentially reduce the energy costs of livestock production, but our study reveals that it is not the trajectory of the global AFS. The use of human-edible crops as feed has grown faster than grazing, and in 2015–2019, it made up 48% of feed input into livestock production (see Table 1).

Even though combating food loss is important for providing more food with less environmental impact, previous studies have found that the largest potential lies in replacing meat and dairy products with plant-based food items (69–71). One study showed how plant-based alternatives to livestock products could provide between 2- and 22-fold more nutritionally similar food per unit of cropland (70). Another estimated that current global crop production is sufficient to provide enough calories, protein, and micronutrients (vitamin A, iron, and zinc) for a world population of 9.7 billion people when crops are fed to people instead of livestock (69). Though, the study recognizes this would require significant structural changes to the world economy and the distribution of food, as well as fundamental changes to diets. Hence, livestock products are, in theory, superfluous in both a nutritional and energetic perspective. The issue is not just a matter of inefficient conversion of human-edible calories. Livestock products have the highest share of energy use in food processing across all products groups. In all regions, it takes up at least 50% of the energy that is used in food processing. So, even if feed could be converted more efficiently into livestock product calories, it will still require a large amount of energy in the downstream processing stages. The (energetic) unsustainability of livestock-based diets is further highlighted by the fact that none of the 20 world regions in our study have EROEI of livestock products above 1. Even in low-income countries, where livestock products make up <10% of the calories in the diet, livestock products are energy sinks.

An increasing demand for biofuels also means an increasing demand for primary crops (72). Two of the largest biofuel producers in the world are United States and Brazil, who make ethanol from maize and sugar cane, respectively. In the period 2015–2019, the EROEIs of maize and sugar cane were 2.7 and 3.7, respectively. Though, this is only the EROEI for producing the crops and not the EROEI of the ethanol used as biofuel. The EROEI of ethanol production is likely to be higher, as the use of by-products from ethanol production (e.g. distillers grains) should be allocated a share of the EEIs. Still, these crops hence constitute viable sources of fuel despite having EROEIs lower than those of fossil fuels (73, 74). Biofuels can replace fossil fuels within AFS to reduce the EEI demand and thus increase the EROEI of the system. Increased biofuel production will, however, either require increased land use or intensification of agriculture. This is obviously problematic in a world where cropland is limited, and intensification often comes at the expense of natural carbon sinks (e.g. rainforest, soil carbon stocks, etc.). One study showed that land constraints (as opposed to labor constraints) were the limiting factor of agricultural production and could only be overcome with larger fossil fuel use and/or environmental impacts (39). Another study indicates that increased agricultural output causes the depletion of accumulated energy stock in nature, in the form of soil nutrients (34). Electrification of agricultural machinery provides an alternative to biofuels that could improve the EROEI of the AFS by significantly reducing the on-farm energy demand (75).

Increasing demand for primary crops comes at the expense of higher environmental costs (e.g. energy use, land use, etc.) and food prices. While livestock products serve a food demand, biofuels serve an energy demand that might be decoupled from AFS. For example, a private jet owner might be willing to pay more for flying on biofuels than households can afford on food. This competition will inevitably lead to a dilemma for governments, who either will have to redistribute wealth in society or increase subsidies for primary crop production to keep prices artificially low. The latter has been practiced in most industrialized countries for decades (6, 76). However, through agricultural subsidies, governments have led the agricultural sector "… by a modernisation paradigm based on specialisation, intensification and scale enlargement," that has "weakened the economic resilience of farms" during the last few decades due to their increased reliance on external (energy) input (77). Departing from this paradigm, governments may promote AFSs that are more resilient and less dependent on fossil fuels. When biofuel production competes with food production for agricultural products, increasing energy prices will spill over into the food market. According to Engel's law, this may have detrimental effects on poorer households, who use a larger share of their budget on food (8). An example is the recent Russo-Ukrainian War and its effect on the world's energy and food markets (8, 78, 79).

Future trajectories

The trajectories shown in Figure 3 raise two important questions regarding the future EROEI of the global AFS.

First, how much will high-income regions increase their EROEI in the coming decades? Current global livestock production causes disproportionate land use, biodiversity loss, and greenhouse gas emissions, all rooted in the inefficient conversion of plant biomass to food calories. This study adds energy use to the list. Attempts at shaping the demand side of the food system, e.g. through national dietary guidelines or the provision of food in schools, have in the past reflected both human health considerations and the interest of domestic food producers. Recently, food policies also aim to reduce environmental impacts of the system (80). However, such attempts have faced backlash from the public and lobbyists from the agricultural industry (81). The argument is often that diets are a personal matter which should not be influenced by governments, even when similar influences by advertisers and lobbyists are uncritically accepted, and past policies did not face the same criticism. If past changes are any guide, improvements in EROEI are more likely due to structural changes and advancements in the supply side of the food system, rather than large-scale dietary changes on the demand side.

The concept of sustainable intensification suggests that agricultural production may increase its outputs while increasing natural capital through integrated pest management, conservation agriculture, integrated crop and biodiversity, pasture and forage, trees, irrigation management, and small or patch systems (82). The feasibility of sustainable intensification on a global level, however, needs more research (83). In addition, the application of digital technologies to agricultural systems is thought capable of improving the economy and sustainability of production (84). Technological improvements in food processing may also reduce both energy dependence and waste of the food processing sector (85). These potential efficiency gains might, however, be pointless from a sustainable food system perspective if, following Jevon's Paradox (86, 87), only serve to satisfy an increasing demand for biofuels and livestock products (69). Nevertheless, if this demand is going to be met regardless, it is better to do so with more efficient practices.

Second, what trajectory might low-income regions take? The varying EROEIs vs GDP per capita trajectories of middle-income regions show that there is more than one path. The combination of high EROEI and relatively high GDP per capita in Eastern Asia provides an optimistic scenario for the future. On the contrary, Western Asia gives a more dire outlook with its low EROEI. As a previous study has shown, technological, demographic, and geographic factors may be important for future development (88).

In addition to these two questions, how severely the ongoing (and worsening) climate change and biodiversity crises will affect these trajectories and AFS in general is unclear. Increased crop losses due to pests, droughts, floods, and storms will increase energy expenditure per eventually harvested crop. Mitigation measures, such as precision farming with better targeted water and fertilizer use and the electrification of farm equipment, would raise energy efficiency. Nevertheless, EROEI is simply an economic indicator. An EROEI >1 is neither a sufficient nor necessary condition for sustainable AFS. Reduced energy use will lead to a faster and more efficient elimination of agricultural CO_2 emissions. Although this study focuses on energy use, our model has the capacity to investigate several other impacts, such as labor, land use, greenhouse gas emissions, biodiversity loss, and raw material extraction. Nexus studies of multiple impact categories using the model would provide a more complete overview of the challenges and potential impact trade-offs in AFS. In-depth agroecosystem analysis is needed to fully grasp the severity of issues at the local level and mitigation options available (89–93).

Materials and methods

The energy output (i.e. the consumed calories) is calculated by converting the reported final demand consumption of food product in tons of biomass in FABIO (18) using global average calorie content of different food commodities (94). FABIO reports food waste in retail and at households separately to the food consumed, and these are not counted as output of the AFS in the EROEI calculation unless specifically mentioned.

The energy input into the AFS is calculated as

$$D_{\text{footprint, FABIO}} = S_{\text{energy,FABIO}} X_{\text{footprint,region}}$$

where $X_{\text{footprint, region}}$ is the biomass upstream production demand calculated and the $S_{\text{energy,FABIO}}$ is the upstream energy intensity of the biomass producing sectors, calculated using standard input–output calculations (95) as

$$X_{\text{footprint, region}} = L_{\text{FABIO}} \widehat{y_{\text{region}}}$$

and

$$S_{\text{energy,FABIO}} = (D_{\text{footprint}} C_{\text{EXIOBASE,FABIO}}) \hat{x}^{-1}$$

where $\widehat{y_{\text{region}}}$ is the final demand vector of a region turned into a diagonal matrix (indicated by the hat), L_{FABIO} is the FABIO Leontief inverse, $\hat{x}^{-1}$ is the FABIO total production vector (diagonalized and then inverted), $C_{\text{EXIOBASE,FABIO}}$ is an allocation matrix, and $D_{\text{footprint}}$ is the upstream energy in the supply chain of the agri-food sectors calculated using EXIOBASE (17) and the hypothetical extraction method (19) as

$$D_{\text{footprint}} = S_{\text{energy}} \begin{pmatrix} H \\ L_{22} A_{21} H \end{pmatrix} (\widehat{y_1} + A_{12} \widehat{L_{22} y_2})$$

with

$$H = (I - A_{11} - A_{12} L_{22} A_{21})^{-1}$$

where S_{energy} is the net energy use stressor in EXIOBASE, I is an identity matrix of the appropriate size, A_{ij} are elements of the EXIOBASE production recipe matrix, and L_{ij} are elements of the of EXIOBASE Leontief inverse (see Section 5.5 in SI 1 for a more detailed derivation and explanation of terms).

$C_{\text{EXIOBASE,FABIO}}$ allocates the upstream energy calculated using EXIOBASE to FABIO by their biomass weight share (i.e. if the "fruit sector" of a region in EXIOBASE has an energy footprint of 100 TJ and FABIO reports that the region produces 4 kg of apples and 6 kg of oranges, then they are allocated 40 and 60 TJ, respectively).

Fertilizer input and its embodied energy have been modeled explicitly using fertilizer use statistics and the life cycle inventory database ecoinvent (96, 97). Adjustments were made to EXIOBASE to avoid double counting the life cycle energy use of the applied fertilizer (see Section 5.6 in SI 1 for more details).

An overview of all data sources used in the study is given in Table 2. In the supplementary information, we provide a more detailed Materials and methods section which includes background for the use of input-output modelling for studying AFS; a description of the system flows and boundaries, as well as the definition of energy used in this study; derivations and explanations of the equations used to calculate the flows; and an overview of adjustments, assumptions, and limitations.

Table 2. Overview of the datasets used in the model and their sources.

Data	Description	Source
FABIO 1.2 (upcoming release)	FABIO is used to model the biomass flows in the agrifood system. Its total production and land-use account is also used to model the fertilizer input.	(98)
EXIOBASE 3.9.2 (upcoming release)	EXIOBASE is used to model the upstream supply chain and the associated energy footprint.	(99)
Fertilizer energy footprint	Ecoinvent is used to get the energy footprint of the fertilizer minerals.	(100)
National fertilizer statistics	Official statistics on the total agricultural use of different fertilizer minerals are used to rescale the values estimated from the crop-specific application rates.	(101)
Fertilizer application rates	The application rates are used to estimate the fertilizer input for each FABIO crop and region.	(96)
GDP and population statistics	The main aggregates statistics are used for GDP and population statistics, which are shown directly in the figures.	(102)
Net capital stock in agriculture	Historical physical investment flows with depreciation modeled using the perpetual inventory method	(45)
Employment in agriculture	Employment indicators based on the International Labor Organization database.	(103)
Calorie multiplier	Calorie multipliers are used to convert the biomass flows in FABIO into energy flows.	(94)

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Supplementary Material

Supplementary material is available at *PNAS Nexus* online.

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Author Contributions

K.R. contributed to conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft, visualization, and project administration. M.B. contributed to conceptualization, software, validation, resources, data curation, and writing—review and editing. E.G.H. contributed to conceptualization, validation, writing—review and editing, and supervision. F.M. contributed to data curation, software, and writing—review and editing. S.T. contributed to data curation and software.

Data Availability

All final data (results) used in the figures and tables presented are provided in the supporting material. All raw data used for the modeling are publicly available and given in Table 2. To create the results at the full level of resolution, one needs a license to the IEA World Extended Energy Balances, which can be obtained from https://www.iea.org/data-and-statistics/data-product/world-energy-balances. However, one can derive all results presented in this paper without the license, apart from the detailed split of each EEI sources presented in Table 1. Code to create the intermediate data and perform the analysis is hosted on GitHub (https://github.com/Kajwan/food-paper).

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