



A Net Energy Analysis of the Global Agriculture, Aquaculture, Fishing and Forestry System

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Abstract

The global agriculture, aquaculture, fishing and forestry (AAFF) energy system is subject to three unsustainable trends: (1) the approaching biophysical limits of AAFF; (2) the role of AAFF as a driver of environmental degradation; and (3) the long-term declining energy efficiency of AAFF due to growing dependence on fossil fuels. In response, we conduct a net energy analysis for the period 1971–2017 and review existing studies to investigate the global AAFF energy system and its vulnerability to the three unsustainable trends from an energetic perspective. We estimate the global AAFF system represents 27.9% of societies energy supply in 2017, with food energy representing 20.8% of societies total energy supply. We find that the net energy-return-on-investment (net EROI) of global AAFF increased from 2.87:1 in 1971 to 4.05:1 in 2017. We suggest that rising net EROI values are being fuelled in part by ‘depleting natures accumulated energy stocks’. We also find that the net energy balance of AAFF increased by 130% in this period, with at the same time a decrease in both the proportion of rural residents and also the proportion of the total population working in AAFF—which decreased from 19.8 to 10.3%. However, this comes at the cost of growing fossil fuel dependency which increased from 43.6 to 62.2%. Given the increasing probability of near-term fossil fuel scarcity, the growing impacts of climate change and environmental degradation, and the approaching biophysical limits of global AAFF, ‘Odum’s hoax’ is likely soon to be revealed.

Keywords EROI · Net energy · Agriculture · Agroecosystem · Social metabolism · Bioenergy

Introduction

Unsustainable Trends in Global Agriculture, Aquaculture, Fishing and Forestry

All organisms must gather sufficient energy from their environment to survive, with sufficiency determined by an organisms basic metabolic requirements for maintenance, growth and reproduction (Brown et al. 2004), along with the energy required to gather energy from its environment (Court 2019). Additionally, to support any organisms in a community not engaged in energy-gathering, a surplus of energy must be gathered. The proportion of energy available as surplus is a key determinant of the viability and complexity of that

community structure (Chaisson 2011; Tainter 2011). Underpinning these relationships are the laws of thermodynamics. Namely that “A living organism represents an open thermodynamic system that continuously exchanges compounds and heat with the environment, performs mechanical work, and disposes of internal entropy production” (Jusup et al. 2017, p. 8). To meet these requirements for energy the human organism has appropriated biomass from the global environment through three main processes throughout history: (a) the hunting, fishing and gathering of wild fauna, flora and fuel; (b) the planned cultivation of these biota through agriculture, aquaculture and forestry; and (c) the extraction of fossil fuels (Fizaine and Court 2016; Hall and Klitgaard 2018). In contrast to other organisms on Earth energy obtained through these processes is utilised through two different metabolisms: (1) endosomatism, where food energy is metabolised within the human body; and 2) exosomatism, where energy is metabolised outside the human body through the combustion of fossil fuels or biofuels to provide heat, induce motion mechanically, generate electricity, or transform matter (Lotka 1956; Mayumi 2009). These

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processes have on one hand been very successful, supporting the growth of the human population which now stands at over 7.6 billion. However, on the other hand, these now dominant processes of biomass appropriation, namely the global agriculture, aquaculture, forestry and fishing (AAFF) energy system are subject to three interconnected and deeply unsustainable trends.

First, after 10,000 years of global AAFF (Stephens et al. 2019) continued growth on our finite planet means we are reaching the biophysical limits of the land, water, and solar energy that we can utilise for AAFF production (Malhi 2014). Measured with the human appropriation of net primary production (HANPP)—the quantity of biomass taken from primary producers (in this case terrestrial plants) in the form of carbon per year—this has doubled in the twentieth century to approximately 25% (Krausmann et al. 2013). As a result, agriculture and forestry now directly utilises 68% of the Earth's terrestrial surface (FAO 2019c), with only 23% of land classified as true wilderness (Watson et al. 2018). Similarly, it has been estimated that humans appropriate 16% of aquatic PP in order to sustain global fisheries, 17–112% over sustainable levels depending on the specific fishery (Chassot et al. 2010), and likely a vast underestimate (Luong et al. 2020). Consequently, only 13% of the world's oceans can now be classified as true marine wilderness (Jones et al. 2018). This highlights the scale of human energy-gathering from the environment, which Smil (2011) terms 'Harvesting the Biosphere'.

Second, is the continued expansion and intensification of AAFF is a key driver of unsustainable environmental degradation (IPBES 2019; Díaz et al. 2019). This includes: climate change, with agriculture, forestry and other land use contributing $21.2 \pm 1.5\%$ of global greenhouse gas (GHG) emissions in 2010 (Tubiello et al. 2015); terrestrial biodiversity loss, which has now exceeded its planetary boundary (Newbold et al. 2016); marine biodiversity loss (Vierros et al. 2017); the radical alteration of the nitrogen cycle, wherein humanity now fixes as much nitrogen as bacteria (Gorman 2013)—with huge ecological impacts (Vitousek et al. 1997); and soil erosion, wherein approximately 35.9 billion tonnes of soil are eroded each year globally (Borrelli et al., 2017). Compounding these pre-existing pressures on the biosphere is population growth; it is predicted that 9.7 billion people will have to be fed, clothed and supplied with energy by 2050 (Berners-Lee et al. 2018). Without major changes to patterns of production and consumption this increased demand for biomass is likely to exacerbate land-use conflicts between food production, biofuel production and ecosystem restoration, likely accelerating environmental degradation (IPCC 2019). Broadly, and from an energetic perspective, this depletes 'nature's accumulated energy stocks', and reduces the flow of energy that agroecosystems

receive from nature's stocks in the form of 'ecosystem services' (Guzman Casado and de Molina 2017).

Third is the decreasing energy efficiency of global AAFF (Jordan 2016), a result of a rapidly growing dependency on fossil fuels, one component of the wider societal transition from a biomass-based energy regime to a fossil fuel based energy regime (Krausmann et al. 2008a, b). Such dependence has now resulted in many agroecosystems becoming a net sink of energy to society rather than a source (Guzman Casado and de Molina 2017), an untenable situation in previous agrarian societies whose survival depended on producing surpluses of biomass energy. The transition to a fossil fuel dependent AAFF system occurred in three main ways: (1) within the agroecosystem, through production practices such as tillage, seeding, irrigation, harvesting etc., which are now dominated by fossil fuel driven machinery, and with the fossil fuel energy use occurring directly; 'on-farm'; (2) through the fossil fuel energy embodied in inputs to global AAFF such as fertilisers, herbicides, and pesticides where fossil fuel energy use occurs indirectly, and 'upstream' (Harchaoui and Chatzimpiros 2018b); and (3) through the increasing dependency of global AAFF's post-production processes on fossil fuels, namely the transport to consumption processes, which occur 'downstream' of the agroecosystem and include transportation, processing, packaging, distribution, retail and household preparation (Infante Amate and de Molina 2013).

Pioneers of environmental sustainability were long aware of these unsustainable trends, including Howard Odum, who wrote in 1971: "A whole generation of citizens thought that the carrying capacity of the earth was proportional to the amount of land under cultivation and that higher efficiencies in using the energy of the sun had arrived. This is a sad hoax, for industrial man no longer eats potatoes made from solar energy, now he eats potatoes partly made of oil" (Odum 2007 [1971]). In the 50 years that have since passed, these three unsustainable trends have deepened, as such that the current AAFF system is at risk of systemic failure in the twenty first century.

The primary subject of this paper are the risks posed by AAFF's growing dependence on fossil fuels, as there is growing evidence that the net energy return on investment (net EROI) of fossil fuels is decreasing, such that we may be approaching a 'net energy cliff' where the availability of fossil fuels to society is rapidly constrained (Brockway et al. 2019). This risk has been identified as a critical uncertainty in assessing the biophysical sustainability of society (Day et al. 2018), and is currently underrecognized in established risk frameworks; where the biophysical risks of climate change, biodiversity loss, freshwater depletion, population growth and soil erosion take centre-stage (UNDRR 2019). Additionally, is the need to rapidly reduce fossil fuel use and associated GHG emissions to prevent dangerous climate

change (Franks and Hadingham 2012), which also places the agri-food system at risk, as failing to do so will result in losses to production (Gaupp et al. 2019; Thiault et al. 2019).

Framework of Energetic Assessment

Given the twin context of (1) potential threats to the global AAF system, and yet (2) the lack of global studies, we set out to assess the sustainability of the global AAF, its role as an energy system and its vulnerability to the three unsustainable trends. To do so, we develop a net energy analysis framework, building on the methodologies developed by biophysical economists (Murphy et al. 2011; Hall 2017; Haberl et al. 2019), those specifically for energy in agroecosystems (Odum 1967; Pimentel et al. 1973; Tello et al. 2015; Guzman Casado and de Molina 2017), and importantly in alignment with the most up-to-date methodology for assessing the energy conversion chain (ECC) of the fossil fuel energy system (Brockway et al. 2019). We conduct an analysis between 1971 and 2017 for which there were three main objectives:

- (1) Determine a methodological structure for conducting a net energy analysis of agriculture, aquaculture, fishing and forestry at a global scale (this is presented in “Developing a Methodological Framework for a Global AAF System Analysis” section).
- (2) Conduct a net energy analysis of global agriculture, aquaculture, fishing and forestry; then situate our results in the context of prior studies (this is given in “Results: An Energetic Overview of the Global AAF Energy System” section).
- (3) Examine the implications of these results in the context of global AAF’s three unsustainable trends (this is contained in Discussion: Examining Global AAF’s Three Unsustainable Trends section).

The two main metrics utilised in NEA are: (i) the net energy balance (NEB), which quantifies the excess or deficit of energy from an energy-gathering process; and (ii) the energy return on energy investment (EROEI or EROI), the ratio between the energy output and input from a system, which describes the efficiency of the energy-gathering process. EROI can be defined in gross or net terms (Heun et al. 2018). In AAF, the net EROI represents the total ‘energy cost’ of biomass produced as food or fuel energy (Guzmán et al. 2018), and as with fossil fuels indicates what proportion of energy is available for the rest of society and the economy. In the context of AAF we define these three metrics in Eqs. 1–3.

$$\text{NEB} \equiv \text{Net Energy Balance} = \text{Gross Energy Output} - (\text{Biomass Inputs} + \text{Non energy Uses} + \text{Losses}) \quad (1)$$

$$\text{Gross EROI} = \frac{\text{Gross Energy Output}}{\text{Total Energy Inputs}} \quad (2)$$

$$\text{Net EROI} = \frac{\text{NEB}}{\text{Total Energy Inputs}} \quad (3)$$

where Net Energy Balance is the total energy produced by AAF minus all biomass inputs to AAF, losses and non-energy biomass uses, Gross Energy Output is Total Energy Produced by AAF in the form of food, feed and fuel. Total Energy Input is the sum total of all energy inputs (food, feed and fuel) to global AAF system Biomass Energy Inputs is the proportion of energy produced by AAF which is re-invested in the system as human food, working animal feed, bioenergy and seed. Losses is the quantity of biomass wasted from production to consumption.

Figure 1 shows the system diagram for this analysis. Energy enters Earth’s geobiosphere through four major flows: solar radiation, relic heat and radiogenic heat, and the dissipation of tidal momentum (Brown et al. 2016). Solar energy is the primary input to the biosphere flowing to ‘nature’s accumulated energy stocks’ (from which flows of energy emerge and are utilised by agroecosystems e.g. pollination services) and renewable energy production. Ancient solar energy is also embodied in fossil fuels. Direct and indirect inputs enter through societies two major energy gathering systems (AAF and fuel) from which primary energy carriers are produced. These final energy carriers then pass through post-production processes and are either re-invested in the energy gathering systems or are returned to the rest of society through either the societal endo or exosomatic metabolisms. In accordance with the second law of thermodynamics energy is lost to the system as waste heat at every stage of this process, which is either trapped within the atmosphere, or emitted as infrared radiation (Kleidon 2010).

Our analysis only considers the energy products (wood fuel/primary solid biofuels) produced by forestry. We choose to adopt the terms: agriculture, aquaculture, fishing and forestry as they are the terms adopted by the FAO and IEA in accordance with the United Nations International Standard Industrial Classification of All Economic Activities Revision 4.

The paper is structured as follows: the methodology is presented in “Developing a Methodological Framework for a Global AAF System Analysis” section, an overview of global AAF based on the results of our analysis is detailed in “Results: An Energetic Overview of the Global AAF Energy System” section, we then proceed to situate the results of our analysis within the context of the three unsustainable trends in “Discussion: Examining Global

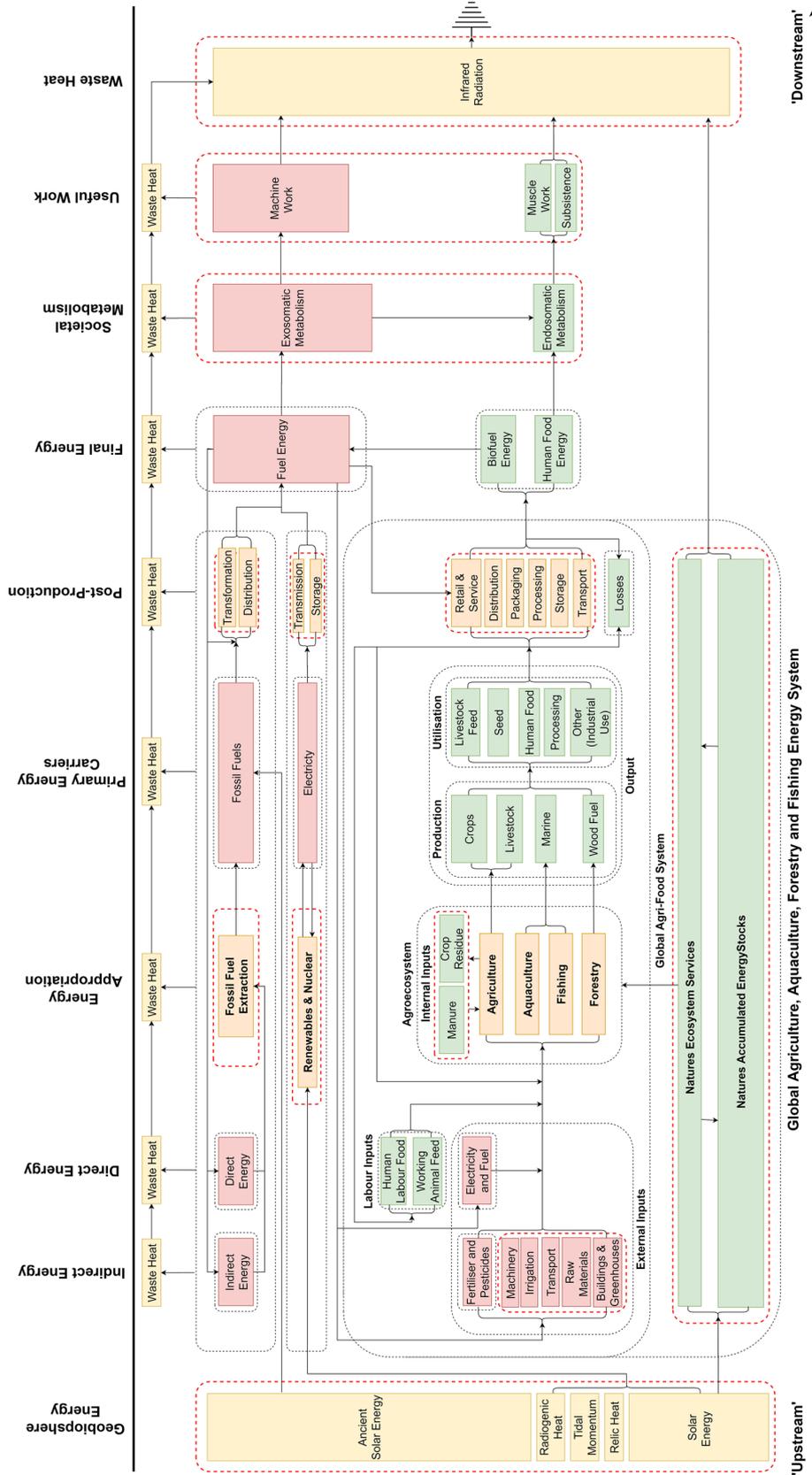


Fig. 1 A system diagram representing the food and fuel energy conversion chain. Green shaded boxes indicate organic processes and associated energy carriers, red shaded boxes indicate inorganic processes and associated energy carriers, orange shading indicate energy appropriation and post-production/transformation systems, yellow shaded boxes indicate energy inputs and outputs to the geosphere, and red dashed lines indicate system components not investigated in this analysis (Color figure online)

AAFF's Three Unsustainable Trends" section, and finally "Conclusions".

Developing a Methodological Framework for a Global AAFF System Analysis

Selecting an EROI Metric and Compatible System Boundary

Research on EROI in agroecosystems is divided into three strands: (i) national or sub-national EROI estimates, (ii) crop-specific EROI estimates and comparisons, and (iii) estimates which compare different production practices (Gingrich et al. 2018a, b), the first strand of which serves as the best framework for our study. Numerous methods exist for

$$\text{Net EROI} = \frac{(\text{Human Food Output (EJ)} + \text{Bioenergy Output (EJ)}) - (\text{Human Labour Food (EJ)} + \text{Bioenergy Input (EJ)})}{(\text{Working Animal Feed and Human Labour Food}) \text{Inputs (EJ)} + \text{External Inputs (EJ)}} \quad (4)$$

calculating the EROI of agroecosystems, for which Guzman Casado and de Molina (2017) provide the most comprehensive guidelines. Their EROI metrics are structured around the three key energy flows in agroecosystems: (i) biomass production (outputs), (ii) external inputs, and (iii) internal inputs (recycled biomass). From these flows, three main EROI metrics are derived by Guzman Casado and de Molina (2017): (1) External Final EROI (EFEROI): the degree to which an agroecosystem is a net sink or source of energy to society; (2) Internal Final EROI (IFEROI): the efficiency of the reuse of biomass in the production of food, and therefore the degree of circularity of the systems metabolism; and (3) Final EROI (FEROI): the combined input–output ratio.

For our purposes, the adoption of an EFEROI-based metric is most appropriate for two reasons, (i) we are assessing the role of AAFF as a sink or source of energy to society, and (ii) insufficient data was available for internal inputs at a global scale. However, confounding this selection is the controversy over the classification of human and animal labour as internal or external inputs, and therefore where to situate them in the EFEROI and IFEROI frameworks. Harchaoui and Chatzimpiros (2018a, b) describe how the majority of EROI studies utilise a methodology which regards "human labour as a through flow and draft animal power as an internal flow"; as it has been argued that the inclusion of animal labour in agroecosystem analysis is unnecessary if the working animals feed is produced within the system, as working animal feed is reflected in the decreased output of the system (Bayliss-Smith 1982). However, Harchaoui and Chatzimpiros (2018a, b) argue that the inclusion of both draft animal feed and farmers food is necessary to reflect the changing composition of agricultural inputs over the course

of industrialisation, from 'self-fuelling' to fossil fuel based fuelling and resultant decrease in agrarian self-sufficiency. They highlight that based on this framework studies which regard working animal feed as an internal input and exclude them from EFEROI calculations underestimate the EROI of pre-Green Revolution agroecosystems.

Therefore, for the purposes of this analysis we adopt an altered EFEROI metric based on Harchaoui and Chatzimpiros (2018a, b) methodology. Additionally, their methodology utilises the *net* production rather than gross production and therefore calculates the net EROI. This allows for analysis of the energy available to the non-farming population. As limited data was available for working animal feed (Output Data Selection and Calculation section), the gross output and gross EROI were incalculable. This lack of working animal feed is therefore automatically absent from the net output.

Subsequently, and in accordance with Eq. 3, the numerator of Eq. 4 for the net EROI is calculated by subtracting the human labour food energy input and bioenergy input from the total human food output and bioenergy output. The denominator is the sum of the food and feed inputs (Labour Inputs section) and the external inputs (External Inputs section), which represent mainly fossil fuel based indirect inputs in the form of fertilisers and pesticides, and direct inputs in the form of electricity and fuel use.

A key reason for the selection of the net EROI metric is that the NEB is consistent in the way it represents the loss of energy as the result of re-investment of food and animal feed energy in AAFF. Conversely, and problematically gross EROI metrics do not fully consider the distinctiveness of different energy carriers; namely (i) biomass-based food, animal feed and fuel, and (ii) predominantly fossil fuel based fuel energy, the investment of which does not reduce the amount of food energy available to society. This distinction must be kept in mind when interpreting gross EROI values. For example, the substitution of one unit of food energy input with one unit of fuel energy input would not change the gross EROI, only a net EROI as the numerator of Eq. 4 would increase.

Input Data Selection and Calculation

In accordance with metrics selected in [Selecting an EROI Metric and Compatible System Boundary](#) section inputs to the global agroecosystem were divided into: (a) external inputs, which were further subdivided into (i) direct energy (energy use which occurs 'on-farm' in the agroecosystem) and (ii) indirect energy (energy use which occurs 'upstream'

and is embodied in inputs used in the agroecosystem); and then (b) labour inputs, which consisted of (i) human labour, and (ii) animal labour. Labour inputs were treated as direct

interpolated to represent each year within that decade and extrapolated to 2020 based on the 2000–2010 trend. Data for fertiliser and pesticide production was then multiplied by the embodied energy value for each year in the 1971–2017 period to produce input estimates (Eqs. 5 and 6).

$$\text{Fertiliser Energy(MJ)} = \text{Fertiliser Production(tonnes)} \times \text{Fertiliser Energy intensity (MJ tonnes}^{-1}\text{)} \quad (5)$$

$$\text{Pesticide Energy(MJ)} = \text{Pesticide Production(tonnes)} \times \text{Pesticide Energy intensity (MJ tonnes}^{-1}\text{)} \quad (6)$$

inputs, but neither internal nor external. For data please see [Data Statement](#) section.

External Inputs

Referring to Fig. 1, direct inputs consisted of electricity and fuel use. Their data was sourced from the International Energy Agency (IEA) extended energy database (2019a), which was organised into two sectors: (i) agriculture and forestry, and (ii) fishing (incl. aquaculture). Electricity and fuel use was subdivided into four categories of total primary energy supply (TPES): (i) Fossil Fuels, (ii) Electricity and Heat, (iii) Bioenergy, (iv) Renewables and Nuclear.

Next, due to a lack of data at the global level, indirect energy inputs were limited to fertiliser and pesticide production in agriculture, with no indirect inputs at all for fishing or forestry.¹ The annual datasets for both fertiliser and pesticide production were derived from FAO (2019a). FAOSTAT provides data for fertiliser production in two datasets: 1961–2002, and 2002–present. The associated metadata warns that methodological differences may produce analytical errors; however, Pellegrini and Fernández (2018) find that the differences between the sets are 2% for nitrogen-based fertilisers, 3% for phosphorus and 15% for potassium, which was deemed negligible for this analysis. Data for pesticide use was only available from 1990, therefore this was extrapolated linearly backwards to provide data from 1971 to 1990.

The embodied energy in fertiliser (nitrogen, phosphorus and potassium) production, along with pesticide use (fungicides, insecticides, herbicides etc.), was derived from Guzman Casado and de Molina (2017) and provided for each decade from 1970 to 2010. These decadal values were

Labour Inputs

Human labour is the key input to AAF as directly ingesting food energy to perform labour is the most fundamental form of metabolism. Historically muscle work from humans and animals was the dominant input in AAF, with fossil fuels becoming the main input only in the twentieth century (Fizaine and Court 2016). Tyedmers (2004) also considers labour a main input to the fishing industry. Fluck (1992) describes the three methods for assessing the human labour input: (i) “partial energy consumed from metabolised food during work”; (ii) “total food energy metabolised during work”; (iii) “total dietary energy consumed”. In this study the “total dietary energy consumed” method was used, as consuming the subsistence number of calories is a pre-requisite for performing labour, and this food is not available to the rest of society.

To calculate the human labour data, the analysis proceeded in several steps. First, data from Steenwyk et al. (in preparation) was utilised for the number of workers in global AAF. Second, data from ILOSTAT was used for the mean working hours for AAF workers, as data was only available from 1991 the 1991–2017 trend was extrapolated backwards to 1971 to complete the time-series. Third, the energy expenditure of human labour was estimated to be 0.45 MJ h⁻¹ based on Cusso et al. (2006), representing 3.6 MJ or 859 kcal 8 h⁻¹ day. As no data was available for how agricultural labour energy has changed over time, this figure was used for the entire 1971–2017 period. Fourth, for subsistence energy the mean recommended calorie intake of 2250 kcal (9.42 MJ) day⁻¹ was utilised. As identified by Guzmán et al. (2018) this methodology does not incorporate the energy that is embodied in the food that agricultural workers consume, and therefore “avoids the problem of circular referencing or double counting”. Equations 7 to 9 show the calculations performed.

$$\text{HumanLabor (MJ)} = \text{Subsistence Energy(MJ)} + \text{Work Energy (MJ)} \quad (7)$$

¹ Indirect AAF inputs omitted due to a lack of complete datasets at the global level include machinery, irrigation, materials, transport, and other infrastructure.

$$\text{Subsistence Energy(MJ)} = 9.42(\text{MJ day}^{-1}) \times 365(\text{days}) \times \text{Number of workers} \quad (8)$$

$$\text{Work Energy(MJ)} = 0.45(\text{MJ h}^{-1}) \times \text{Mean work hours}(\text{h week}^{-1}) \times 52(\text{weeks}) \times \text{Workers}. \quad (9)$$

Next, calculations to estimate work energy for global draught animals for the period 1971–2017 were completed based on several steps. First, estimates for the number of global working animals in AAFF were obtained from Steenwyk et al. (in preparation). Second, data for the feed requirements of working animals was obtained from Stout (2012), who calculated the gross energy of daily feed required for asses, bovines, dromedary camels, horses, and mules. He estimated that for every 100 kg of bodyweight the animal consumes 2 kg of hay day⁻¹, which has an energy density of 15.65 MJ kg⁻¹. As an estimate for buffalo was absent the average weight of a buffalo was obtained from FAO (2000) and then multiplied by the feed requirement. Aguilera et al. (2015) argues that as working animals have no anthropogenically assigned function within the global agroecosystem other than for labour, animals subsistence energy on working and non-working days should be used in addition to the energy required to perform labour—a methodology consistent with the human labour input. As Stout (2012) estimate assumes all working animals are draught animals (which perform the hardest labour) the daily feed estimates were multiplied by a factor of 0.775, as Kander and Warde (2009) estimate that animals performing average labour require 22.5% less feed than animals performing hard labour. Additionally, Gonzalez and Guzmán (2006) estimate that working animals perform labour for an average of 188 days year⁻¹, with 177 non-working days. Consequently the energy required was reduced by a factor of 0.45 on non-working days as Kander and Warde (2009) estimate that the subsistence energy requirement is 55% lower than hard labour. Equations 10–13 display the calculation method for animal labour, these calculations were performed for each working animal species from 1971 to 2017.

$$\text{Daily Feed Energy(MJ day}^{-1}) = \frac{\text{Animal Mass(kg)}}{100(\text{kg})} \times 2(\text{kg day}^{-1}) \times 15.65(\text{MJ kg}^{-1}) \quad (10)$$

$$\text{Non working Days (MJ)} = \text{Daily Feed Energy(MJ day}^{-1}) \times 0.45 \times 177(\text{days}) \quad (11)$$

$$\text{Working Days (MJ)} = \text{Daily Feed Energy(MJ day}^{-1}) \times 0.775 \times 188(\text{days}) \quad (12)$$

$$\text{Total Working Animal Energy(MJ)} = \text{Non working Days(MJ)} + \text{Working Days (MJ)} \quad (13)$$

Post-production Inputs

This analysis does not include post-production processes ‘downstream’ from the commodity stage such as transport, storage, processing, packaging, distribution, and retail and service due to data availability. Whilst the processing phase could be assessed for food products through the IEA’s ‘Manufacturing - Food and Tobacco’ sector (processing in this framework), as other stages would have been omitted, along with the processing stage for biofuels we chose not to utilise this data.

Internal Inputs

Internal inputs within agriculture consist of crop residue, manure, cover crops, and depending on the choice of classification, livestock feed and animal labour (Tello et al. 2015); however, due to a lack of data at the global level the calculation of these were beyond the scope of this study. FAOSTAT records crop residue data, but for only a limited number of crops. Whilst estimates for crop residue may be calculated utilising the harvest index of crop plants, the proportion of crop residue that is returned to the soil, as opposed to utilised as animal feed, exported as fuel, or burnt is unknown. Wirsenius (2000) provides the only global study detailing the flows of agricultural biomass in this regard; however, as he only assessed the 1992–1994 period we could not utilise his data to construct a time-series which reflected changes to use of internal inputs. FAOSTAT records the nitrogen content of manure stocks at a global level, but in the absence of comprehensive crop residue data this was not utilised.

Whilst an estimate for the labour performed by working animals was conducted, the source of their feed is a major

source of uncertainty. The proportion of feed that is produced on-farm vs off-farm is unknown. FAOSTAT does record output production destined for livestock feed; however, this is only a proportion of total livestock and working animal feed for two reasons: (1) FAOSTAT also does not record crops produced for direct consumption by animals; and (2) the FAOSTAT's food balance data records only 77 out of 97 energy carriers. Whilst the feed requirement could be calculated for livestock using feed conversion ratios, the lack of crop data for direct feed would invalidate an estimate.

Natural Stocks and Flows of Energy

The calculation of natural stocks and flows of energy (Fig. 1) is an even greater challenge than quantifying internal inputs at the global scale, as changes to these natural stocks and flows of energy are reflected in complex phenomena including: climate change induced precipitation decline (Rojas et al. 2019), pollinator decline (Burkle et al. 2013), the erosion of soils (van Zelm et al. 2018), the depletion of groundwater (Mukherjee et al. 2018), widespread deforestation (Curtis et al. 2018) and marine ecosystem collapse and fishery depletion (Jones et al. 2018). To assess this an *emergy* analysis of AAF is required. Emergy studies form a body of literature relatively distinct from EROI studies. Pioneered by Odum (1996) emergy analysis allows for a more precise characterisation of the sustainability of an agroecosystem as it recognises the predominantly solar origins of energy in the biosphere (Fig. 1), and corrects for this by applying solar transformity factors to each stock or flow, standardising them in terms of solar energy (seJ). Using emergy analysis to assess the relative scale of natural to human inputs in modern AAF Pérez-Soba et al. (2019) identified that the ratio of human inputs (fossil fuel based) to natural inputs is 4.2:1 in EU agriculture, highlighting the quantity of work done by fossil fuels and therefore dependence.

Land

Data for land area utilised by agricultural land was obtained from the HYDE database (Goldewijk et al. 2011). Decadal values were available from 1970 to 2000, values for years in between were interpolated linearly, data for each year was available from 2000 to 2016 and extrapolated to 2017 based on the 2000–2016 trend.

Output Data Selection and Calculation

Agriculture Output

Data for food outputs was obtained the Food and Agriculture Organisation of the United Nations (FAO) statistical database (FAOSTAT) 'Food Balance' section (FAO 2019b).

In this section only food products are recorded, and similar food products are aggregated leading to a total of only 97 outputs. However, whilst this section provides less data granularity than the 'Production' section it does split total food production into several 'utilisation' categories: livestock feed (77/97 items), seed (39/97 items), other (97/97 items), losses (81/97 items), and processing (68/97 items). Along with the quantity of total production which is ultimately used for human food (96/97 items). Where 'Processing' refers to the quantities of output utilised for processing for human consumption i.e. wheat to flour; 'Other' refers to output utilised for industrial non-food processes such as bio-fuels and soap; and 'Losses' refers to the output loss between after appropriation (e.g. the farm gate) to the end-use (e.g. household). This disaggregation allows for partial assessment of the production which does not end up as human food.

As FAOSTAT does not record all animal feed "Cereal crops harvested for hay or harvested green for food, feed or silage or used for grazing are therefore excluded.... Data relate to vegetable crops grown mainly for human consumption" (FAO 2019d), the total food fed to livestock and working animals, and therefore true total (or gross) output is incalculable; however, as we are conducting a net energy analysis, this omission is acceptable as it does not alter the quantity of food available for farming and non-farming human population.

Aquaculture and Fishing Output

Data for marine output was split into fishing and aquaculture production, and obtained from the FAO's Fisheries and Aquaculture Department's statistical database, and accessed through the software package 'FishstatJ' (FAO 2019a). Marine output was split into 11 groups: Aquatic Animals NEI, Aquatic Mammals, Aquatic Plants, Cephalopods, Crustaceans, Demersal Marine Fish, Freshwater and Diadromous Fish, Marine Fish NEI, Molluscs excl. Cephalopods, Pelagic Marine Fish and Others. Representative energy densities were then applied to each group, with all groups then standardised into simply aquaculture or fishing output.

Bioenergy Output

Bioenergy is the term used to refer to biomass energy utilised for exosomatic purposes. For this analysis the IEA categories of: Peat, Peat products, Primary solid biofuels, Biogases, Biogasoline, Biodiesels, Bio jet kerosene, Other liquid biofuels, Non-specified primary biofuels and waste and Charcoal used in accordance with IEA (2019b), then condensed into four categories: (1) Primary Solid Biofuels, Charcoal and Waste, (2) Peat and peat products, (3) Liquid Biofuels, and (4) Biogases. Data for bioenergy production

was obtained from the International Energy Agency’s (IEA) World Extended Energy Balances 2019 (2019a). Data for world production was used for bioenergy production, whilst the total primary energy supply data was used for inputs to AAFF.

AAFF Energy Output

Data for the energy densities of agriculture, aquaculture and fishing outputs were obtained through three main sources: (1) The Animal Feed Resources Information System (AFRIS) or Feedipedia (FAO et al. 2019), (2) *Energy in Agroecosystems* by Guzman Casado and de Molina (2017), and (3) USDA FoodData Central (USDA 2019). For the small number of AAFF outputs that were not included

Metabolism Composition

As AAFF returns energy to society as both food and fuel, the balance between endo and exosomatism in societies metabolism must be examined. Equations 17–21 show the calculations performed to derive the energy produced by society for the exosomatic and endosomatic metabolisms, along with the proportion of food energy AAFF produces and proportion of total energy produced as food energy by society. Data from IEA (2019a) was used for bioenergy, and the world primary energy supply was used for the exosomatic energy supply.

$$\text{Endosomatic Energy(EJ)} = \text{Total Food Output (EJ)} \quad (17)$$

$$\text{Exosomatic Energy(EJ)} = \text{World Primary Energy Supply (EJ)} \quad (18)$$

$$\text{Food Share of AAFF Energy (\%)} = \left(\frac{\text{Endosomatic Energy (EJ)}}{\text{Total AAFF Output (EJ)}} \right) \times 100 \quad (19)$$

$$\text{AAFF Share of Total Energy (\%)} = \left(\frac{\text{Total AAFF Output (EJ)}}{\text{Endosomatic Energy(EJ)} + \text{Exosomatic Energy(EJ)}} \right) \times 100 \quad (20)$$

$$\text{Food Share of AAFF Energy (\%)} = \left(\frac{\text{Endosomatic Energy (EJ)}}{\text{Endosomatic Energy(EJ)} + \text{Exosomatic Energy (EJ)}} \right) \times 100 \quad (21)$$

in these main sources, values were taken from their closest equivalent, or individual sources (see [Data Statement](#) section).

To calculate AAFF output in energetic terms the output (in tonnes) for each product was multiplied by the embodied energy value (MJ tonnes⁻¹) for each year in the 1971–2017 period (Eq. 14). The sum of each output category was then calculated, then the ‘Other’ output (representing non-food uses) subtracted to give the total output of food energy (Eq. 15). Following on, the Total AAFF Output which is a measure of both the food and fuel) is equal to the sum of the Food Energy and Biofuel Energy (Eq. 16).

Net Energy Analysis

The equations for analysing the NEB and the net EROI of AAFF were developed based on Brockway et al.’s (2019) methodology for analysing the fossil fuel energy system. Brockway et al. (2019) provides estimates for fossil fuel EROI at two stages: (1) primary (EROI_{PRIM}), which includes energy used in production, and energy embodied in products used in extraction; and (2) final (EROI_{FIN}), which includes the additional energy invested in transformation and distribution, and the energy embodied in products used in transformation and distribution. As we did not analyse

$$\text{AAFF Output (MJ)} = \text{Output (tonnes)} \times \text{Embodied Energy (MJ tonne)}^{-1} \quad (14)$$

$$\text{Food Energy (EJ)} = \text{Total Production (EJ)} - \text{Other (EJ)} \quad (15)$$

$$\text{Total AAFF Output (EJ)} = \text{Food Energy (EJ)} + \text{Biofuel Energy (EJ)} \quad (16)$$

post-production processes in global AAFF, analogous with the transformation and distribution processes in the fossil fuel energy system (Fig. 1), our analysis calculated the net EROI of global AAFF to the Primary energy stage.

Equations 22 and 23 detail the calculations performed to calculate the NEB and net EROI of global AAFF.

$$\text{NEB} = E_T - (E_{HL} + E_{AL} + E_{Bio}) \quad (22)$$

$$\text{NetEROI} = \frac{\text{NEB}}{(E_{\text{AL}} + E_{\text{HL}}) + (E_{\text{dE}} + E_{\text{iE}})} \quad (23)$$

Input Weighting: Fossil Fuel Dependency and Self-Fuelling

To assess the transition from ‘self-fuelling’ to fossil fuel based fuelling (and change in agrarian self-sufficiency) the proportion of total inputs that were fossil fuel based was calculated (Eq. 24), along with the proportion of inputs which derive from AAF: self-fuelling (Eq. 25).

$$\text{Fossil Fuel Dependency}(\%) = \left(\frac{E_{\text{dE}} + E_{\text{iE}}}{(E_{\text{AL}} + E_{\text{HL}}) + (E_{\text{dE}} + E_{\text{iE}})} \right) \times 100 \quad (24)$$

$$\text{Self Fuelling}(\%) = \left(\frac{E_{\text{AL}} + E_{\text{HL}} + E_{\text{bio}}}{(E_{\text{AL}} + E_{\text{HL}}) + (E_{\text{dE}} + E_{\text{iE}})} \right) \times 100 \quad (25)$$

where E_{T} is Total Human Food Output from AAF, E_{HL} is Human Labour input to AAF, E_{AL} is Animal Labour input to AAF, E_{dE} is Direct energy inputs to AAF (incl. Bio-energy), E_{iE} is Indirect inputs to AAF, E_{bio} is Bioenergy Input to AAF.

Methodological Limitations

There are several limitations and consequently opportunities for this methodology, primarily by collating data for elements of the system unable to be assessed in this analysis (see Fig. 1). The two distinct groups of EROI estimates that the review studies display (Fig. 5), pre-1950 and post-1950, indicates that the period of this study (1971–2017) is insufficient in order to capture how the EROI of world AAF changed as the result of industrialisation. This is demonstrated by Harchaoui and Chatzimpiros (2018a, b) who identified that by 1960 in France 50% of agricultural energy use was already fossil fuel based. The lack of data pre-1971 for energy use, and pre-1961 for agricultural outputs prevents this analysis.

Regarding inputs the most critical area for improvement is the disaggregation of agriculture, aquaculture, fishing and forestry. This was not possible in this analysis as the IEA’s electricity and fuel consumption (direct energy) data is aggregated into two sectors: (i) agriculture and forestry, and (ii) fishing (incl. aquaculture); along with labour data which was aggregated into a single AAF group by the ILO and Steenwyk et al. (in preparation). To better assess the composition of societies metabolism AAF must also be split into food and biofuel production. Additionally, estimates for the EROI of other energy systems including renewable energy and nuclear energy to the final stage in accordance with Brockway et al.’s (2019) methodology must be calculated to

facilitate a robust and complete analysis of societies energy systems and therefore energetic metabolism.

The key limitation is the incomplete set of indirect inputs, likely resulting in an overestimate of the NEB and EROI of AAF. Indirect inputs omitted from this analysis include: raw materials, irrigation infrastructure, machinery, transport, greenhouses & other infrastructure, research and development, and other ancillary services. Additionally, this analysis does not include downstream process such as transport, processing, distribution, retail, household consumption and waste (Infante Amate and de Molina 2013), preventing the calculation of total energy cost of delivering food or bioenergy to its ‘point of use’.

There are three uncertainties limitations with human labour inputs. First, labour inputs are not homogenous, they vary greatly based on the crop grown and the production practices. Second, the labour inputs will have likely decreased over time as the result of agricultural mechanisation. Third, the number of agricultural workers is an estimation based on Steenwyk et al. (in preparation) reconstruction of ILO and regional data.

Results: An Energetic Overview of the Global AAF Energy System

First, we present inputs (Inputs section), then outputs (Outputs section); then results of the net energy analysis (Net Energy Analysis Results section); and finally, the results of a review of previous agroecosystem analysis studies (A Review of Agroecosystem Analysis Studies section). Summary tables are found in the Appendix.

Inputs

Referring to Fig. 2 we find between 1971 and 2017 the food required for human labour increased by 15%. This minor increase is reflected in population growth balancing the decrease in the share of the global working population working in AAF, which decreased from 19.8 to 10.3% as human labour was replaced with work done by fossil fuels. The feed input required for working animal labour decreased by only 4%, which reflects the global trend towards the mechanisation of traction work, and the increasing fossil fuel dependency of agriculture (Net Energy Analysis Results section). Studies which assess animal labour in agriculture over a longer period, including Harchaoui and Chatzimpiros (2018a, b) detail that the animal labour was already substituted by machinery as the dominant energy source between 1940 and 1970, before the period of our study. However, this trend is not consistent globally, with many developing regions showing positive trends. In North America and Western Europe draft animal labour was almost completely

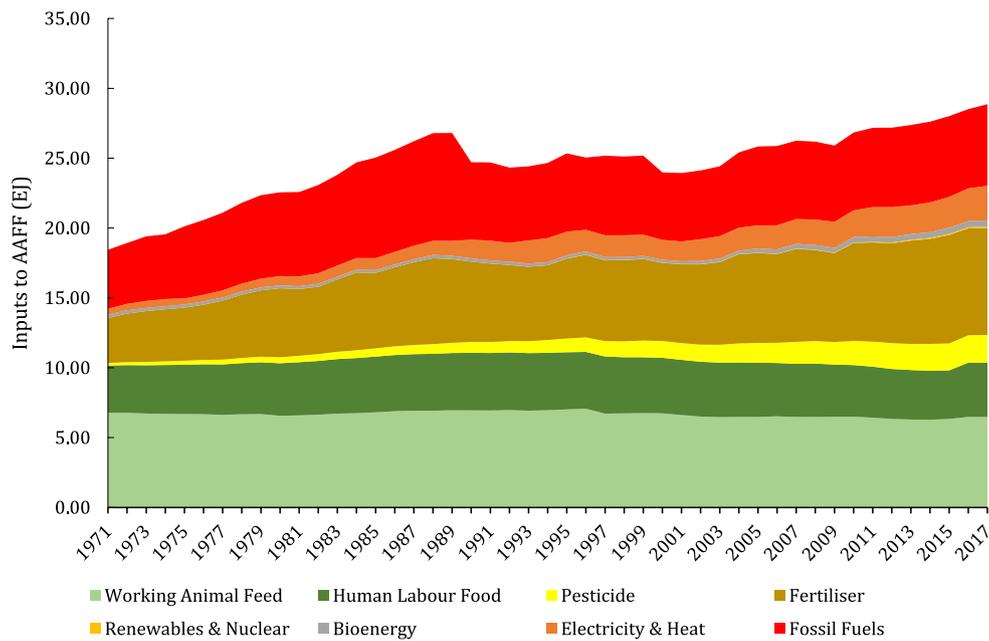


Fig. 2 Inputs to the global AAFF energy system from 1971 to 2017 (EJ). Note data for pesticides was extrapolated pre-1990

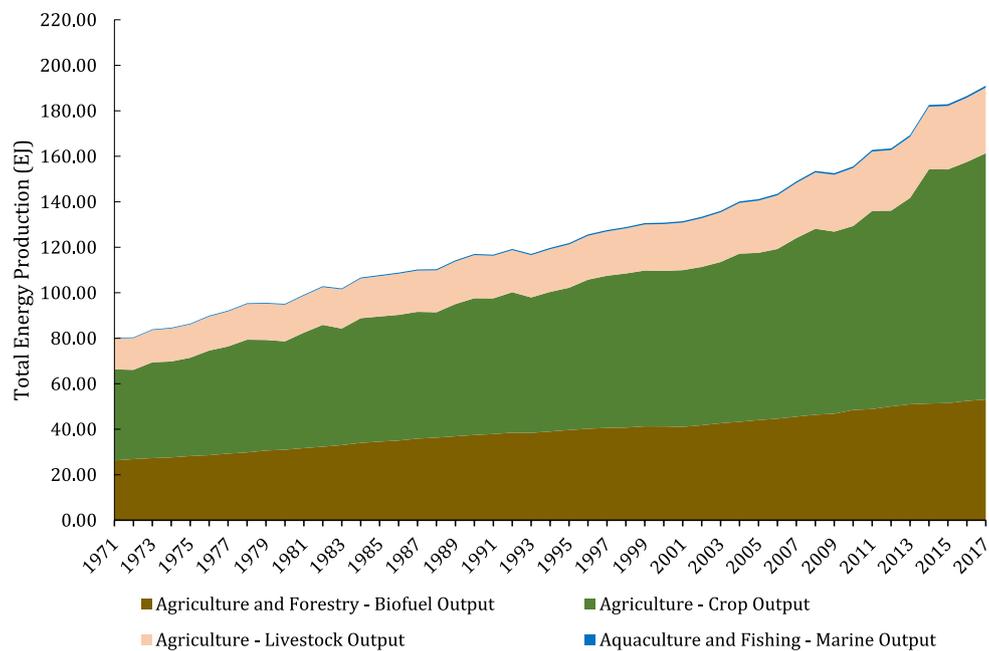


Fig. 3 Total gross production output from the global AAFF energy system from 1971 to 2017 (EJ)

substituted by 1970, but in the rest of the world muscle work performed by animals still remains a major input of energy to agriculture (Steenwyk et al. in preparation).

In contrast to the human and animal inputs, fossil fuel use in AAFF increased by 38%, fossil fuel based electricity and heat increased by 492%, bioenergy increased by 89%, and

renewables and nuclear increased by 11,600% though only from 0.001 to 0.10 EJ. This can be unequivocally attributed to the increased mechanisation in agriculture (Pellegrini and Fernández 2018); whilst not analysed, the expansion of irrigation in agriculture (Sauer et al. 2010); an increase in the number of motorised fishing vessels and total fishing effort

(Anticamara et al. 2011), and finally the continued mechanisation of forestry (Silversides 1984; Kirk et al. 1997; Beuk et al. 2007). Pesticide inputs increased by 948% over the study period, whilst fertiliser inputs increased more slowly by 137%, reflecting the ongoing diffusion of Green Revolution agricultural practices globally (Verma 2015). The relative proportions of electricity and fuel, fertilisers, and pesticides is representative of inputs at the national level as reflected by Norton et al.'s (2011) comprehensive review of agricultural systems and crops in New Zealand—amongst others.

The magnitude of fossil fuel use, and pesticide and fertiliser production varied considerably despite the overall positive trend. In particular electricity and fuel consumption declines sharply during the 1989–1990 period (predominantly fossil fuels), peaking at 7.72 EJ in 1989 then decreasing to 5.54 EJ by 1990. Further investigation attributed this to a sharp drop in agriculture/forestry energy use data to the Soviet Union (up to and including 1989) and the Former Soviet Union (FSU) states (from 1990 onwards), a conclusion supported in the literature (Price et al. 1998; Federico 2008). There may be various reasons for this sharp difference within pre/post-Soviet Union, but the further investigation/speculation on this is not within the remit of this paper, given the limited impact on overall results.

Outputs

Figure 3 shows the gross production (output) from global AAF. Crop refers to the output of plant biomass from agriculture only, similarly livestock refers to the output of animal biomass from agriculture only (addressed in [Agriculture: Crop and Livestock Output](#) section). Biofuels includes the production of wood fuel and primary solid biofuels from forestry and biofuel production from agriculture (addressed in [Agriculture and Forestry: Biofuel Output](#) section). Marine refers to output from both aquaculture and fishing (addressed in [Aquaculture and Fishing: Marine Output](#) section).

Agriculture: Crop and Livestock Output

We find total gross crop output (production) represented the majority of growth in AAF output, increasing by 201% as is shown in Fig. 6. However, human food crop output only increased by 154%, reflecting the growing proportion of crops utilised as animal feed (which increased by 93%) and for other industrial uses (which increased by 1110%, Fig. 6, see [Appendix](#)).

Two potential factors are the increase in area of crop land (9.63%), and human labour (15%) increase; however, given that total crop production increased by 201%, other factors must have contributed to this. The increases to fertiliser use, pesticide use, and exosomatic energy consumption

(Table 2) are potential factors, however other unassessed factors such as a large increase in irrigation, and importantly the development of high-yielding crop cultivars are potential factors. Evenson and Gollin (2003) estimate that for the 1961–1980 and 1981–2000 periods the growth in agricultural production in developing countries was the result of: (1) improved crop cultivars, contributing 17% and 40%; (2) land use expansion, contributing 20% and 0%; and (3) input intensification, contributing 63% and 60%, respectively. Also assessing the factors that contributed to the growth in global agricultural output Fuglie (2015) identified that in 1961 input intensification was the largest factor contributing to growth (at approximately 2%). However, input intensification and overall growth declined until 1990, then between 1991 and 2012 total factor productivity (a measure of the technical efficiency of resource use) was the largest factor contributing to growth. Whilst irrigation and area expansion contributed a relatively small proportion of growth between 1961 and 2012 (below 0.5% each per year).

Importantly studies must also address the land released from working animal feed production due to mechanisation, which Harchaoui and Chatzimpiros (2018a, b) estimated to be 3 million ha in France between 1955 and 1975 for oats alone; or the land released from nitrogen-fixing cover crops by fossil fuel based nitrogenous fertilisers which they estimated to be a further 3 million ha from the 1960s until present. Adjusting the data to account for the effects of land release from improved crop cultivars on output is beyond the scope of this analysis. However, it is highly likely that this would result in an increase in output.

Total gross livestock output increased by 189%, whilst livestock output for human food increased by 131%, and the area for grazing land grew by only 7.27% (Table 3). Therefore, despite regional extensification such as the deforestation of the Amazon rainforest for cattle pasture (Bowman et al. 2012), the majority of increase in livestock output must be due to intensification. The growth in feedlot operations was a major form of intensification, partly evidenced by the 93% increase in livestock and poultry feed (Table 2). Feedlot operations increased production by rearing livestock in concentrated areas and using crops as their main feed. These operations became more viable over the course of the twentieth century due to cheaper and more abundant grain. Feedlots also facilitated an increase in the consumption of beef, which was previously lower as dairy production was too valuable (Hubbs 2010). This is evidenced by the increase in livestock feed (Table 2), which increased by 93% (though there is no data for silage etc., [Agriculture Output](#) section). This increase is lower than the increase in livestock output, indicating that feed may be used more efficiently, achieved through livestock breeding. For example, in the USA the average market age of a broiler chicken has decreased from ~55 days in 1971, to ~47 days

in 2017. Whilst the average market weight has increased from ~1.6 kg in 1971, to ~2.8 kg in 2017 (National Chicken Council 2020). A key effect of this breeding is to increase the feed conversion efficiency (FCE) of livestock production—the percentage of feed calories to livestock production calories. However, despite improvements in efficiency livestock rearing is still an energy inefficient process, and a major cause of the declining EROI of many agroecosystems (Cattaneo et al. 2018), with Shepon et al. (2016) calculating that the FCE for pigs is only 9%, poultry is 13%, eggs and dairy are 17%, and beef is 3%. Furthermore, maximum FCE's are subject to physiological limits, making future gains in livestock output through efficiency improvements unlikely (Tallentire et al. 2018).

Agriculture and Forestry: Biofuel Output

Gross bioenergy output increased by 102%, with large increases in biogases (38,983%) and liquid biofuels (8293%), a smaller percentage increase in primary solid biofuels (82%) and a decrease in the extraction of peat and peat products (−87%, Table 2). Despite a lower percentage increase, primary solid biofuels still represented the majority of bioenergy output in 2017, at 47.98 EJ of 53.06 EJ of total biofuel production. The increase in biofuels derived from agriculture is reflected in the change in agricultural output destined for industrial uses ('Other'), which increased from 1.34 to 16.16 EJ (1110%, Table 2; Fig. 6). However, the causes of the increase in primary solid biofuels are unclear. The area of forestry land decreased from 4128×10^6 ha to 3999×10^6 ha between 1990 and 2017 according to the FAO (2019c). This indicates that either: (1) there was an intensification of forestry management practices which increased the yields of timber products, (2) that an increasing proportion of timber was being used for primary solid biofuels rather than for construction purposes, or (3) that more wood fuel is entering the market from areas outside those officially recorded.

Aquaculture and Fishing: Marine Output

In contrast to agriculture and forestry the 43% increase in total gross fishing output was facilitated by considerable extensification. Swartz et al. (2010) highlight how whilst world agricultural production doubled between 1961 and 1995 with only a 10% increase in area, the 240% increase in fishery catches over the same period required a 400% increase in the area exploited by fisheries, which now cover over 55% of the earth's oceanic area—four times that of agriculture (Kroodsma et al. 2018). To accomplish this expansion a 1% increase in the total fishing effort (calculated from the energy use of fishing vessels) occurred each year between 1970 and 2010 (Anticamara et al. 2011). However, this is

likely an underestimate given that only reported catches are represented in FAO data. Underreported catches include recreational fishery catches (Freire et al. 2020), artisanal catches, subsistence catches and illegal catches, bycatch/discards (Zeller et al. 2018), and finally catch used as bait which re-enters aquaculture and fishing as an internal input. By reconstructing catches Pauly and Zeller (2016) found that true catches are likely to be 53% higher than reported data. Importantly, fishing catches peaked in 1996 at 0.46 EJ, declining to 0.37 EJ by 2017. After 1996 any further gains in gross marine output were facilitated by aquaculture which increased by 2801% between 1971 and 2017.

Losses

In terms of losses FAOSTAT records that there was a 297% increase between 1971 and 2017 (based on 81/97 outputs), compared to the 179% increase in total food production. They assess waste from production to the household, omitting "Losses occurring before and during harvest are excluded. Waste from both edible and inedible parts of the commodity occurring in the household is also excluded". This may explain why this estimate is lower than those in the literature, with total global food waste estimated to be 33.3% by the FAO (2019d). When considering waste at every stage from farm-to-fork, including: unharvested crop residues, transportation and storage, livestock production losses, processing losses, animal production and distribution losses, consumer waste and overconsumption; total waste has been estimated to be as high as 94%. However, when excluding unharvested crop residue (which is often not suitable for human consumption and is an important part of the fertility cycle) total loss from crop production to the consumption stage is estimated to be 44% (Alexander et al. 2017). Depending on the boundaries used for waste both the NEB and net EROI estimates may vary greatly. Forestry waste estimates were unavailable, as were estimates for fishing bycatch.

The Composition of the Societal Metabolism

The proportion of energy produced as food for societies endosomatic metabolism remained relatively stable, only increasing from 18.6 to 19%. The percentage of food energy produced by AAFP increased as a share of total energetic production from 67.2 to 72.2% (Table 4). This indicates that biofuel production increased at a slower rate than food production. AAFP's share of total world energy production decreased slightly, from 27.7 to 26.3%.

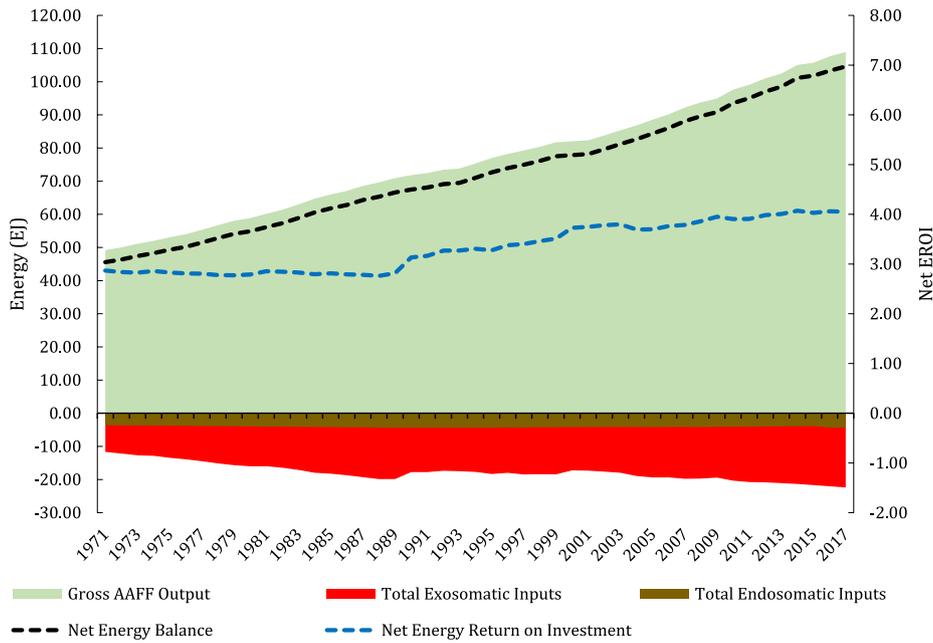


Fig. 4 The gross AAFF output, total exosomatic inputs (electricity and fuels and fertilisers and pesticides), total endosomatic inputs (human and animal labour, net energy balance and net EROI of global AAFF)

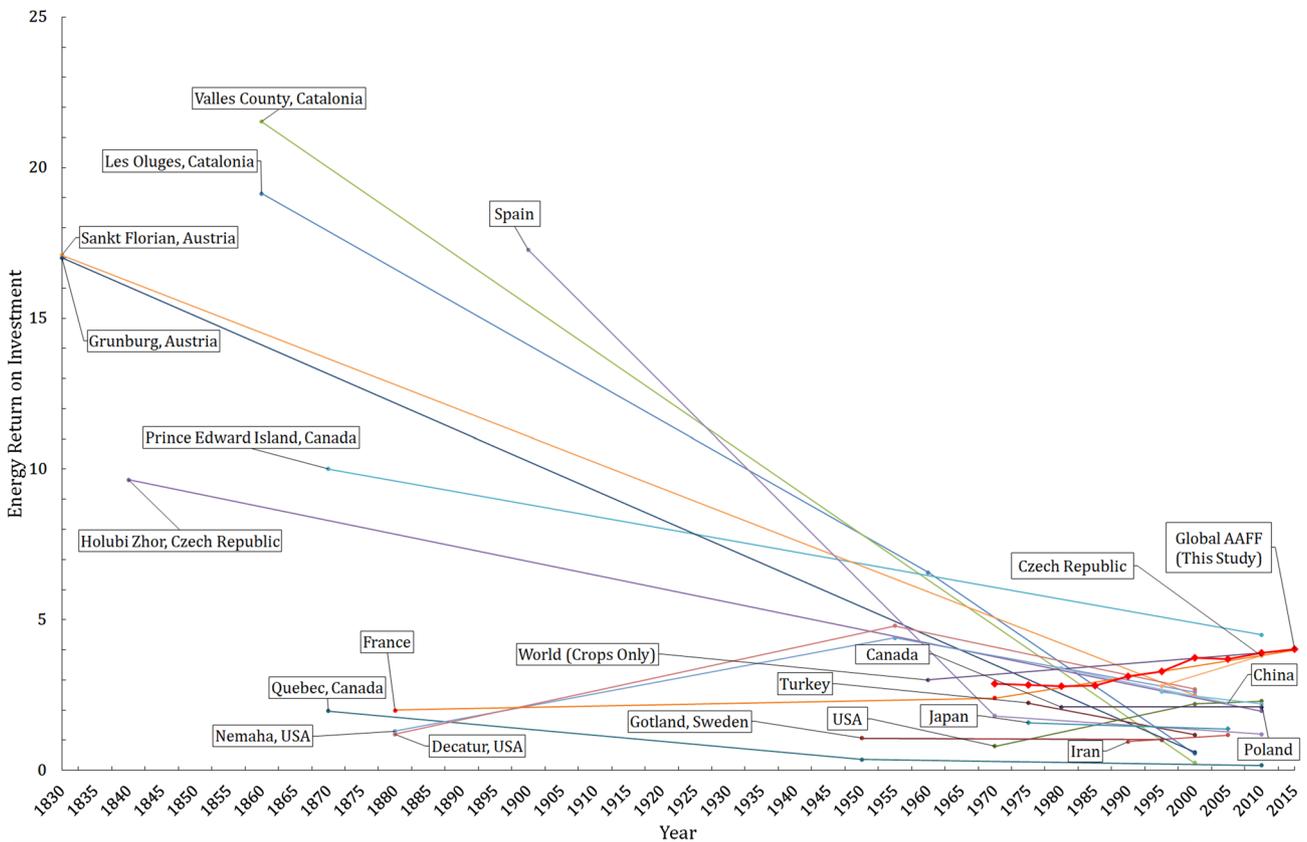


Fig. 5 The review of the estimates for the gross EROI of regional agroecosystems from selected studies (a subset of those in Table 1). Exceptions are the Net EROI of France and the Net EROI of global AAFF calculated in this analysis. This figure omits forestry, aquaculture and fishing agroecosystems as there were insufficient studies estimating how their EROI changed over time

Net Energy Analysis Results

As shown in Fig. 2, both human and animal labour inputs remained relatively constant over the study period (+15% and -4%, respectively), in contrast to the 82% increase in electricity and fuel use and 183% increase in fertiliser and pesticide use. However, fossil fuel inputs continued to substitute work done by human and animal labourers, which is reflected in the percentage of the total population working in AAFP, which decreased from 19.8 to 10.3%; meaning that in 1971 roughly 1 person was able to support for 4 other persons globally, whilst in 2017 this had increased to 9 persons. This transition is also reflected in the proportion of the population living in rural areas, which decreased from 63 to 45% (Table 3). This change in the composition of inputs to AAFP was quantified by the fossil fuel dependency metric, which increased from 44 to 66%, and self-fuelling (the proportion of inputs to AAFP deriving from AAFP) which decreased from 56.4 to 37.5% (Table 4). Total AAFP output increased by 138%, in line with the NEB increased by 130% (Fig. 4).

This analysis found that the net EROI of global AAFP increased from 2.87:1 to 4.05:1 between 1971 and 2017, which perhaps seems surprising given the increased use of fossil fuel based inputs. This trend is displayed in context with other agroecosystem studies in [A Review of Agroecosystem Analysis Studies](#) section and Fig. 5. The likely reasons for this increase are set out and discussed in [Is the Energy Efficiency of Global AAFP Declining as a Result of Fossil Fuel Dependency?](#) section.

A Review of Agroecosystem Analysis Studies

To provide context for our study, we surveyed a range of studies for agricultural systems which reported EFEROI-focussed EROI metrics.² These studies covered varying periods between 1830 and 2015 and which are summarised in Table 1. Several key features stand out. First, owing to the complexity of the global agroecosystem and lack of global data, research on the NEB and EROI of AAFP agroecosystems has predominantly occurred at local and national scales (Guzman Casado and de Molina 2017), with only one global study, which assessed crop production for the 54 major crop producing countries (Pellegrini and Fernández 2018). Second, the studies surveyed generally suggest low (single figure) and declining EROI values in the latter half of the twentieth century. Third, regarding methods, the majority

² With two exceptions: China (Cao et al. 2010) and Japan (Gasparatos 2011) for which the EROI was calculated based on published data, as the reported EROI values from these studies included internal inputs such as crop residue which were not considered in this analysis. Table 1 details the inputs assessed for these and all studies.

of studies adopt a gross EROI metric (see Eq. 2). Last, the studies utilise predominantly external inputs (e.g. fertiliser), as these cross agroecosystem boundaries meaning data is more readily available than internal inputs utilised internally within agroecosystems (e.g. crop residue), as these are not frequently exchanged in the market economy. All estimates consider both direct energy (electricity and fuel consumption), along with selected indirect inputs (e.g. fertiliser), a limited number of studies assess the energy embodied in post-production processes. Importantly, no studies yet capture the full range of both direct and indirect inputs, utilisation outputs which act as losses (not used as food or fuel), or the energy invested in post-production processes.

Discussion: Examining Global AAFP's Three Unsustainable Trends

To examine the sustainability of global AAFP we structure our analysis around the three key unsustainable trends: (1) the approaching biophysical limits of AAFP; (2) the role of AAFP as a driver of environmental degradation; and (3) the declining energy efficiency of AAFP due to growing fossil fuel dependency; reflecting on whether our results provide evidence to support these trends from an energetic perspective in Sects. 4.1, 4.2 and in particular [Is the Energy Efficiency of Global AAFP Declining as a Result of Fossil Fuel Dependency?](#) section.

Is Global AAFP Approaching Biophysical Limits?

Focussing on agriculture, and although our analysis primarily considered flows of energy within the global AAFP system as opposed to its interactions with the environment, we posit that the greatest threat posed by global AAFP in exceeding the Earth's biophysical limits is biofuel production. The continued decline of the EROI of fossil fuels (Brockway et al. 2019), and growing impacts of climate change will increase the need to produce low-carbon liquid fuels for transport, and other biofuels for electricity generation. This is reflected in future mitigation pathways emphasising the role of bioenergy carbon capture and storage (BECCS) as a negative emissions technology (IPCC 2019). However, the carbon-neutrality of biofuels is highly questionable (Giampietro 2015), as is the role of BECCS as a feasible source of net energy to society (Fajardy and Dowell 2018). Importantly the potential expansion of biofuel production has several biophysical limitations.

The scale of the potential impacts of an increase in biofuel production is highlighted by the historical change of the composition of societies metabolism (Sect. 3.3.5). In pre-industrial societies biomass constituted 95–100% of the energy supply; however, the rapid expansion of fossil fuel

Table 1 Summary of EROI estimates of local, national, continental and global agricultural systems, along with the associated direct and indirect external inputs, utilisation losses and post-production inputs used to generate the reported EROI metric

Study location	Selected period	EROI values	Post-1950 Increase	Direct and indirect external inputs, utilisation losses and post-production inputs										Source							
				Direct		Indirect			Utilisation			Post-production									
				Electricity & Fuel	Human Labour	Animal Labour	Fertilisers	Pesticides	Irrigation	Machinery	Buildings	R & D Services	Waste		Live-stock	Seed	Processing	Distribution	Retail & Service	Household	
Austria	1950–1995	1.07 → 1.02		✓	✓	✓	✓														Krausmann et al. (2003)
Canada	1981–2009	2.1 → 2.1		✓		✓	✓				✓										Hamilton et al. (2013)
Canada	2010–2013 (Period)	0.8		✓		✓	✓														Adetona and Layzell (2019)
China	1978–2004	3.38 → 2.22		✓	✓	✓	✓	✓			✓										Cao et al. (2010)
Czech Republic	1993–2012	2.8 → 3.8	✓	✓	✓	✓	✓	✓													Grešlová et al. (2019)
Decatur, USA	1880–1954–1997	1.2 → 4.8 → 2.7		✓	✓	✓	✓	✓			✓										Gingrich, et al. (2018a, b)
Denmark	2004–2007 (Period)	0.25		✓		✓	✓	✓			✓										Markussen and Østergård, (2013)
EU27 (Crops Only)	2003–2005 (Period)	1.93		✓	✓	✓	✓	✓			✓										Pérez-Soba et al. (2015)
France	1882–1971–2017	2 → 2.4 → 4	✓	✓	✓	✓	✓	✓			✓										Harchaoui and Chatzimpiros (2018b)
Gotland, Sweden	1972	1.19		✓	✓	✓	✓	✓			✓										Zucchetto and Jansson (1979)
Grunburg, Austria	1830–2000	17.0 → 0.6		✓	✓	✓	✓	✓			✓										Gingrich et al. (2018a, b)
Holubi, Zhor, Czech Republic	1840–2012	9.65 → 1.97		✓	✓	✓	✓	✓			✓										Fránková and Cattaneo (2018)
Iran	1990–2006	0.95 → 1.17	✓	✓	✓	✓	✓	✓			✓										Beheshi Tabar et al. (2010)
Japan	1975–2005	1.58 → 1.37		✓	✓	✓	✓	✓			✓										Gasparatos (2011)
Les Oluges, Catalonia	1860–1959–1999	19.1 → 6.57 → 0.55		✓	✓	✓	✓	✓			✓										Diez et al. (2018)

Table 1 (continued)

Study location	Selected period	EROI values	Post-1950 Increase	Direct and indirect external inputs, utilisation losses and post-production inputs										Source				
				Direct		Indirect			Utilisation			Post-production						
				Electricity & Fuel	Human Labour	Animal Labour	Fertilisers	Pesticides	Irrigation	Machinery	Buildings	R & D Services	Waste		Live-stock Feed	Seed	Processing	Distribution
Nemaha, USA	1880–1954–1997	1.3 → 4.4 → 2.6		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Gingrich et al. (2018a, b)
Poland	1993–2012	2.6 → 2.2		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Grešlová et al. (2019)
Prince Edward Island, Canada	1870–2010	10.0 → 4.5		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	MacFadyen and Watson (2018)
Quebec, Canada	1871–1951–2011	1.97 → 0.36 → 0.16		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Parcerisas and Dupras (2018)
Sankt Florian, Austria	1830–2000	17.1 → 2.5		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Gingrich et al. (2018a, b)
Spain	1900–1970–2008	17.3 → 1.80 → 1.20		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Guzmán et al. (2018)
Spain	2000 (Period)	0.135		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Infante Amate and de Molina (2013)
Turkey	1975–2000	2.23 → 1.18		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Ozkan et al. (2004)
USA	1970–2000–2009	0.8 → 2.2 → 2.3	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Hamilton et al. (2013)
Valles County, Catalonia	1860–1999	21.5 → 0.25		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Galán et al. (2016)
World (Crops Only)	1961–2014	3.00 → 4.00	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Pellegrini and Fernández (2018)
Global AAFB	1971–2017	2.87 → 4.05	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	This study

use during the industrial revolution decreased this proportion to 10–30% (Krausmann et al. 2008a, b). Our results indicate that biomass energy (from AAF) represented 27.7% of societies total energy supply in 2017, with the food energy component of this representing 18.6% of societies total energy supply (Table 4).

Any future demand for biomass to replace fossil fuels will be limited by the finite supply of agricultural land. This is likely to result in land-use conflicts, as biofuel production must compete with both natural ecosystems and food production (IPCC 2019). Krausmann et al. (2013) estimates that in a scenario where biofuels are relied upon to substitute fossil fuels the HANPP could increase to 44% due to their low power density, and therefore high land requirements (de Castro et al. 2014). This would accelerate the deterioration and loss of natural ecosystems, and further undermine the capacity of the natural environment to support AAF. Furthermore, any further expansion of food or biofuel production will likely be limited by freshwater resources, with Schyns et al. (2019) finding that society is currently utilising 56% of maximum sustainable freshwater resources, and is already overshooting this in many regions. Biofuels as an energy source are particularly water intensive, as emphasised by their low Energy Return on Water Investment (EROWI) compared to fossil fuels and renewable energy technologies (RET's; Mulder et al. 2010).

Biofuel production is also characterised by low EROI values, especially relative to historic fossil fuel EROI values. Reviewing bioenergy EROI estimates Rana et al. (2020) find gross EROI values for bioenergy production systems ranging from 0.08 to 1.84:1 for synthetic natural gas from microalgae, to 14.7–22.4:1 for biogas from corn. Assessing rapeseed production for biodiesel in Europe van Duren et al. (2015) concluded that the maximum gross EROI was 2.2:1. Though further work is required to align all studies system boundaries, ensuring no overestimations and no 'apples-to-oranges' comparisons (Murphy et al. 2016; Raugei 2019), these estimates evidence the limited capacity of biofuel production to maintain a sufficient net energy supply to society.

Despite these pressures, there is considerable scope for improving the efficiency with which current agricultural land is utilised, and therefore to remain within Earth's biophysical limits, particularly through reductions in both waste (Sect. 3.2.4) and animal agriculture. As highlighted in Sect. 3.2.1, the conversion of plant-based livestock feed into meat and dairy involves energetic losses of approximately 10% between trophic levels. As such, reducing the quantity of food suitable for human consumption that is fed to animals, and/or the land used for pasture could simultaneously increase self-sufficiency, food, water, and land availability, along with decreasing numerous adverse environmental impacts (Shepon et al. 2018; Poore and Nemecek 2018; Berners-Lee et al. 2018; Rizvi et al. 2018; Springmann et al.

2018; Willett et al. 2019; Karlsson and Rööös 2019). However, a reduction in livestock consumption is not a one-size-fits-all solution. Numerous criteria must be considered in a local context including: the fertility benefit of livestock for the agroecosystem, the suitability of land for arable agriculture, the ecological role of livestock in the agroecosystem, and any additional purposes of the livestock.

Is Global AAF Driving Environmental Degradation?

Providing a useful framework to assess agricultural sustainability in energetic terms is Guzman Casado and de Molina's (2017) definition of a sustainable agroecosystem: "... an agroecosystem should provide an optimal level of biomass production over time without deteriorating the basis of its funds elements whilst maintaining the optimal provision of ecosystem services". This agroecological paradigm recognises that well-functioning agroecosystems are produced through the correct management of the complex interactions between natural and anthropic stocks and flows of biomass, minerals, water and energy (Smith et al. 2017), with the goal of energy efficiency, system stability and longevity. At the contrasting end of the spectrum is the reductionist framework of industrial agriculture, which regards land as an inorganic substrate for production, through which inputs enter and outputs emerge, with the goal of output maximisation (Etingoff 2016).

Jordan (2016) describes how these contrasting approaches are potentially irreconcilable based on the principles of thermodynamics—specifically the maximum power principle. Referencing Odum and Pinkerton (1955) he describes how non-equilibrium thermodynamic systems (NET's; systems which self-organise, and degrade energy sources to maintain a higher state of organisation and lower entropy relative to their environment) operate at an energy use efficiency that is optimised for maximum power output, an efficiency which is always lower than the maximum efficiency. Thus, there can be two aims: maximising output, or maximising efficiency. He demonstrates that as agroecosystems are self-organising NET's they are subject to this law and tend to seek maximum power output. Practically this is reflected in the incentivisation for: short-term survival, as a response to marketplace competition, and most importantly as the effects of unsustainability aren't immediately reflected in yields and therefore income. This also contributes to the understanding of the third unsustainable trend of global AAF (its sub-optimal energy efficiency).

To more accurately characterise the sustainability and energy efficiency of global AAF the two organic, or natural forms of energy in agroecosystems must be considered: (1) the internal inputs: and (2) the energy embodied in natural inputs (ecosystem services or nature's accumulated energy stocks). Regarding crop residue Smil (1999), describes how

no nation keeps comprehensive statistics on its production and fate. He also describes how a large proportion of this phytomass does not return fertility to the soil due to combustion on-farm, or export from the agroecosystem as feed or fuel, breaking the ‘law of return’ of organic agriculture (Howard 2006)—a loss that goes unrecorded. Numerous studies provide evidence that inorganic fertilisers are increasingly replacing and/or supplementing recycled biomass for fertilisation at the regional level. Cao et al. (2010) calculates that ‘biological inputs’ (crop residue and manure) to Chinese agriculture represented 41% of the total input energy in 1978, decreasing to 32% in 2004. Assessing a greater timespan Galán et al. (2016) found that the recycled biomass energy within the Vallès County agroecosystem (Catalonia, Spain) decreased from 95% in 1860 to 10% in 1999. If this trend is present at the global scale it would represent a decline in the sustainability of global AAFP due to a reduction in the circularity of energy and nutrient cycling, Cattaneo et al. (2018) refers to this as the “loss of the circular bioeconomy”.

Additionally, it well-established that agriculture, aquaculture, fishing and forestry are degrading the natural environment at the global scale (IPBES 2019), and appropriating ever-increasing quantities of NPP (Krausmann et al. 2013). Considering that a key result of this analysis was the increase in the net EROI of global AAFP between 1971 and 2017 (Fig. 4), this appears to go against the third posited unsustainable trend of global AAFP, as this apparent improvement in energy efficiency indicates an improvement in sustainability. However, given the variation in studies from the literature, and as this study did not take into account internal inputs and natural flows of energy, it cannot be concluded that the increase in EROI is truly more efficient, and therefore more sustainable (Cattaneo et al. 2018; Pérez-Soba et al. 2019). Conversely it is highly likely that the increase in the net EROI of global AAFP is being fuelled in part by ‘depleting natures accumulated energy stocks’.

Is the Energy Efficiency of Global AAFP Declining as a Result of Fossil Fuel Dependency?

To identify whether the EROI of global AAFP is declining as a result of increased fossil fuel dependency two points are important to discuss: the aggregate EROI level, and the trend. First, we estimate that the net EROI of world AAFP for 1971–2017 was in the region of the surveyed studies which covered the post-1950 period (Fig. 5). This was expected due to the similar range of inputs utilised as detailed in Table 1. Second, regarding trends over time two distinct groupings can be seen from Fig. 5: (i) pre-1950, for which 7 out of 11 studies assessing this period had EROI’s over 9.65:1; and (ii) post-1950, where only one study’s values exceeded 5:1 (Les Oluges, Catalonia in 1960), indicating

that some pre-Green Revolution agroecosystems were substantially more energy efficient than modern agroecosystems. However, many of these studies didn’t consider working animal feed, or cover cropping land requirements likely underestimating the increase in net production and therefore the net EROI over time.

We identified that the net EROI of global AAFP increased by 41% (Table 4, Sect. 3.4) from 2.87:1 to 4.05:1, first decreasing during the 1970s and 1980s, then generally increasing from 1990 until 2017. In contrast to our results, the EROI for 11 out of the 16 studies which assessed a post-1950 period decreased in the second half of the twentieth century, implying that our results may be inaccurate. However, as detailed in Table 1 many of these EROI estimates do not adopt a net energy perspective which would further reduce the net energy available to society. The exception is Harchaoui and Chatzimpiros (2018b) who assessed France, showing that yield gains and the land released from animal feed and cover cropping outweighed increasing fossil fuel inputs, leading to the net EROI increasing from 2:1 in 1882 to 2.4:1 in 1971, then to 4:1 in 2017—mirroring our results. This trend was mirrored by Pellegrini and Fernández (2018), the only global study, which assessed the energy use efficiency (EUE; analogous with gross EROI) of global crop production by region. They found that the global EUE in the 1960s was 2.5–3.5:1, first decreasing during the early 1980s as the result of rapid input intensification, then increasing towards 3.5–4.5:1 in the 2010s. This was due to the rate of energy input decreasing from 298–330 to 53–43 PJ year⁻¹, whilst outputs continued to increase by ~645 PJ year⁻¹ consistently, thus outpacing input growth and leading to increased EUE. This trend is also mirrored by Fuglie (2015) who assigns output growth to input intensification until 1990, then an increase in total factor productivity (analogous with resource efficiency) until 2012.

There are several likely reasons for the increase in the net EROI of Global AAFP. First, the increased traction efficiency of machinery over animal labour reduced the energy invested to perform tillage, and importantly changed the form of this energy from feed to fossil fuels increasing net production. Second, improved feed conversion efficiencies for livestock production reduced feed costs, and released further land from feed production; together with land release from cover cropping due to the use of artificial fertilisers, this led to decrease in self-fuelling and increase in net output (Harchaoui and Chatzimpiros 2018b). Third, the more efficient use of inputs including improved nitrogen use efficiency and the fuel efficiency of machinery reduced the fossil fuel based inputs to AAFP in situ (Kim et al. 2018). Fourth, the increase in the efficiency of input production through improved nitrogen synthesis and other fertiliser production reduced the energy embodied in inputs utilised in AAFP (Guzman Casado and de Molina 2017). Last, a range

of agronomic and crop physiological developments including improved crop cultivars, improved agronomic tools and practices, the CO₂ fertilisation effect and associated increase in water use efficiency (Pellegrini and Fernández 2018). As our analysis omitted indirect inputs such as the energy embodied in irrigation infrastructure, machinery, materials, transport etc., their effect on the EROI trend of AAFB could not be examined, but inclusion of these inputs would have reduced EROI values. Further decomposition of the contributing factors to the increase in net EROI is beyond the scope of this study.

Compared to agriculture, both fishing and aquaculture are substantially less energy efficient, and a sink of energy to society. Tyedmers et al. (2005) assessed global fisheries in 2004 and estimated that the EROI was 0.08:1. Guillen et al. (2016) assessed European fisheries between 2002 and 2008, finding that the EROI increased from 0.102:1 to 0.114:1. Similarly, Vázquez-Rowe et al. (2014) highlight that the EROI of aquaculture ranged from 0.014:1 for shrimp production in Thailand, to 0.10–0.15:1 for Scandinavian Mussel production. The lower EROI of aquaculture is a result of need for both plant and wild fish-based feed (for carnivorous fish) in addition to the infrastructure energy costs, and so whilst aquaculture remains a net producer of marine output it is not without cost, still depending on fishing output, and a major cause of habitat modification and other ecological impacts (Naylor et al. 2000).

In contrast to both agriculture and fishing EROI values for forestry (biofuels) are high. Pandur et al. (2015) estimate that the EROI of wood fuels is 64.3:1, and wood chip 24.9:1. Similarly, Buonocore et al. (2014) estimate that the EROI of timber is 51.9:1, and wood chip 28.1:1. Considering these high EROI values for wood fuels relative to the reviewed studies (Table 1) and proportion of output consisting of primary solid biofuels it can be inferred that the EROI of agriculture is likely to be lower than the aggregate AAFB values.

The net EROI values for AAFB calculated in this analysis are considerably lower than net EROI values to the primary stage for the fossil fuel energy system, interestingly the trends also differ with the net EROI of the fossil fuel energy system decreasing from 37.4:1 to 28.7:1 between 1995 and 2011, furthermore when analysed to the final stage net EROI values have decreased from 6:1 to 5.4:1 (Brockway et al. 2019). This phenomenon reflects the ease with which a stock of non-renewable energy resources may be exploited relative to the cultivation of biomass based on the slow accumulation of solar energy (Schramski et al. 2015). However, as with will all non-renewable stocks fossil fuels are subject to diminishing returns. Given the interconnected nature of the AAFB and fossil fuel energy systems one would expect to see the net EROI decline of the fossil fuel energy system reflected in the AAFB energy system. As with other studies we did not consider the increasing quantities of fossil

fuel energy embodied in the fossil fuel inputs to AAFB, this was therefore not reflected in our net EROI metric, but if included would have dampened the positive net EROI trend we identified.

Conclusions

In this study we developed a framework for the net energy analysis of global AAFB, and completed a net energy calculations for 1971–2017. We found that the net EROI of global AAFB increased from 2.87:1 in 1971 to 4.05:1 in 2017, with the net energy balance increasing from 45.6 to 104.6 EJ. The fossil fuel dependency of AAFB increased in tandem, from 43.6 to 62.2%, with a corresponding decrease in the proportion of people working in AAFB and proportion of rural residents—evidencing the association between urbanisation and the global farm surplus.

The magnitude of our net EROI values is similar to estimates identified in the literature, whilst the rising trend (3:1 to 4:1) finds support in 5 out of the 11 studies which assessed a post-1950 period, including the only other global study—which also has the closest methodology to ours. We identify several possible reasons for the increase in net EROI, including that as global AAFB is a key driver of environmental degradation, these increases to net EROI are also likely being fuelled in part by depleting ‘natures accumulated energy stocks’. Given the increasing probability of near-term fossil fuel scarcity, growing impacts of climate change and environmental degradation and approaching biophysical limits of global AAFB, ‘Odum’s hoax’ (Sect. 1.1) is likely to be revealed.

Data Statement

The extended energy input datasets (including bioenergy) were obtained under licence from the IEA. The IEA World Energy Statistics and Balances can be downloaded with institutional or other user licence from <https://doi.org/10.1787/enestats-data-en>.

Data for agricultural output was obtained freely from FAOSTAT at <https://www.fao.org/faostat/en/#home>.

Data for land use was freely obtained from the HYDE database <https://themasites.pbl.nl/tridion/en/themasites/hyde/download/index-2.html>.

Data for aquaculture and fishing output was obtained from the FAO Fisheries and Aquaculture Department’s statistical database, through the software package FishstatJ <https://www.fao.org/fishery/statistics/software/fishstatj/en>.

Data for employment in agriculture, aquaculture, fishing and forestry and the number of working animals

was obtained with permission from Steenwyk et al. (in preparation).

Data for the energy embodied in AAFF outputs was obtained from three main sources: (1) The Animal Feed Resources Information System (AFRIS) or Feedipedia (FAO et al. 2019) at <https://www.feedipedia.org/>; (2) *Energy in Agroecosystems* by Guzman Casado and de Molina (2017); and (3) The USDA FoodData Central (USDA 2019) at <https://fdc.nal.usda.gov/>.

The data repository for this study (Marshall and Brockway 2020) can be found at <https://doi.org/10.5518/822>. Data included within this depository includes: summary statistics, output data, and fertiliser and pesticide inputs. Data obtained under licence has been omitted.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflicts of interest.

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Appendix

Figure 6 details the 'Utilisation' side of the FAO's Food Balance data. Total production is greater than the sum of the utilisation categories as the 'Production' and 'Utilisation' data are not entirely reconcilable. For this analysis we chose to report the gross output from agriculture using the 'Total production', and the net output using the 'Human food' component of the FAO's Food Balance data which is an imputed category of data, but greater than the 'Processing' category from the 'Utilisation' data which refers to commodities destined for human food. We also use the 'Other' data to ensure that we are not double counting the Total Gross AAFF Production when including biofuel data from the IEA.

Tables 2, 3 and 4 provide a summary of the metrics used in this analysis for the years 1971 and 2017.

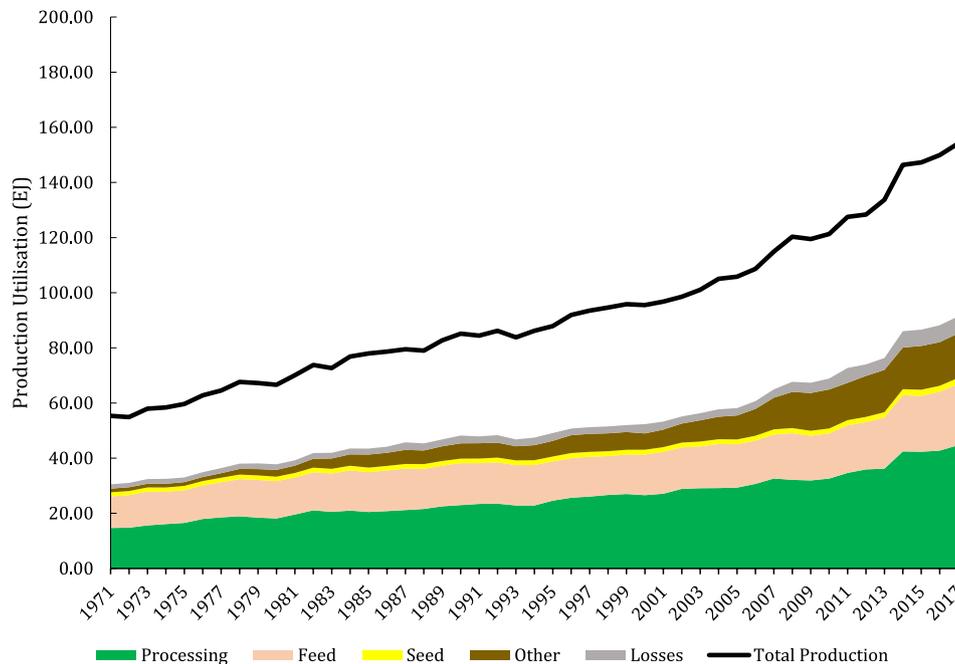


Fig. 6 Output utilisation (destinations of production) in gross terms for agriculture, aquaculture and fishing 1971 to 2017 (EJ), primary solid biofuels (incl. the products of forestry) are not represented here as these outputs are not recorded in the food balance data

Table 2 A summary of inputs and outputs to global AAFF for 1971 and 2017

Category	Sub-category	Item	Units	1971	2017	Change (%)
Inputs	Labour	Human Labour Food	EJ	3.38	3.88	15
		Working Animal Feed	EJ	6.78	6.48	- 4
	Direct	Fossil Fuels	EJ	4.22	5.84	38
		Electricity and Heat	EJ	0.42	2.49	492
		Bioenergy	EJ	0.24	0.45	89
		Renewables and Nuclear	EJ	0.001	0.10	11,600
		Total Electricity and Fuel	EJ	4.88	8.87	82
	Indirect	Fertiliser	EJ	3.22	7.64	137
		Pesticides	EJ	0.19	1.99	948
		Total Fertiliser and Pesticide	EJ	3.41	9.63	183
	Total inputs		EJ	18.45	28.86	56
Outputs	Production	Crops	EJ	41.35	124.44	201
		Livestock	EJ	9.98	28.87	189
		Marine	EJ	0.37	0.83	127
		Total Production	EJ	55.33	154.14	179
	Marine Production (FishstatJ)	Aquaculture	EJ	0.01	0.37	2801
		Fishing	EJ	0.31	0.44	43
		Total Marine	EJ	0.32	0.82	153
	Utilisation	Feed	EJ	11.46	22.09	93
		Other	EJ	1.34	16.16	1110
		Processing	EJ	14.67	44.70	205
		Seed	EJ	1.49	2.31	55
		Losses	EJ	1.55	6.17	297
	Production: Human Food	Crops	EJ	12.67	32.2	154
		Livestock	EJ	9.98	23.0	131
		Marine	EJ	0.19	0.69	265
		Total Human Food	EJ	22.85	55.88	145
	Biofuels	Peat and Peat Products	EJ	0.67	0.10	- 85
		Primary Solid Biofuels, Charcoal and Waste	EJ	25.62	47.98	87
		Biogases	EJ	0.003	1.33	38,983
		Liquid Biofuels	EJ	0.04	3.65	8293
Total Biofuels		EJ	26.33	53.06	102	
	Total gross AAFF output		EJ	80.33	191.05	138

Pesticide data was extrapolated back in time from 1989 to 1971. All outputs are given in Gross terms

Table 3 A summary of population, employment and land use metrics from 1971 to 2017

Category	Sub-category	Item	Units	1971	2017	Change (%)
Land		Crop Land	$\times 10^6$ ha	1423	1560	9.63
		Grazing Land	$\times 10^6$ ha	3054	3275	7.27
		Forestry Land	$\times 10^6$ ha	4128	3999	- 3.13
Population and employment	Population	Total Population	Billion Persons	3.78	7.55	100
		Rural Population	Billion Persons	2.39	3.41	43
		Urban Population	Billion Persons	1.39	4.14	198
		Proportion of Population in Rural Areas	%	63.22	45.18	- 18.04
	Employment	AAFF Workers	Billion Persons	0.75	0.78	4
		Proportion Total Population Working in AAFF	%	19.77	10.31	- 9.46

Table 4 A summary of metrics detailing the balance between endosomatism and exosomatism in the societal metabolism, along with the results of a net energy analysis, and metrics describing the weighting of inputs to AAFF

Category	Sub-Category	Item	Units	1971	2017	Change (%)
Metabolism Composition	Exosomatic Energy	World Production	EJ	236.20	587.61	149
		Biofuel Energy	EJ	26.33	53.06	102
		Non-biofuel Energy	EJ	209.87	534.55	155
	Endosomatic Energy	Food Energy	EJ	54.00	137.98	156
		Total World Energy Production	World Production + Food Energy	EJ	290	726
	Metrics	Food Share of AAFF Total Output	%	67.2	72.2	5.00
		Food Share of Total World Energy Production	%	18.6	19.0	0.41
AAFF Share of Total World Energy Production		%	27.7	26.3	-1.35	
Analysis	Net Energy Analysis	NEB	EJ	45.6	104.6	130
		Net EROI	Ratio (:1)	2.87	4.05	41
	Input Weighting	FF Dependency	%	43.6	62.2	18.6
		Self-Fuelling	%	56.4	37.5	-18.9

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