



Article Edible Energy Production and Energy Return on Investment—Long-Term Analysis of Global Changes

Bartłomiej Bajan^{1,*}, Joanna Łukasiewicz¹, Agnieszka Poczta-Wajda² and Walenty Poczta¹

- ¹ Department of Economics and Economic Policy in Agribusiness, Faculty of Economics, Poznan University of Life Sciences, 60-637 Poznan, Poland; asialukasiewicz1@gmail.com (J.Ł.); poczta@up.poznan.pl (W.P.)
- ² Department of Macroeconomics and Agricultural Economics, Institute of Economics, Poznan University of
- Economics and Business, 61-875 Poznan, Poland; Agnieszka.Poczta-Wajda@ue.poznan.pl

* Correspondence: bartlomiej.bajan@up.poznan.pl; Tel.: +48-61-846-6379

Abstract: The projected increase in the world's population requires an increase in the production of edible energy that would meet the associated increased demand for food. However, food production is strongly dependent on the use of energy, mainly from fossil fuels, the extraction of which requires increasing input due to the depletion of the most easily accessible deposits. According to numerous estimations, the world's energy production will be dependent on fossil fuels at least to 2050. Therefore, it is vital to increase the energy efficiency of production, including food production. One method to measure energy efficiency is the energy return on investment (EROI), which is the ratio of the amount of energy produced to the amount of energy consumed in the production process. The literature lacks comparable EROI calculations concerning global food production and the existing studies only include crop production. The aim of this study was to calculate the EROI of edible crop and animal production in the long term worldwide and to indicate the relationships resulting from its changes. The research takes into account edible crop and animal production in agriculture and the direct consumption of fossil fuels and electricity. The analysis showed that although the most underdeveloped regions have the highest EROI, the production of edible energy there is usually insufficient to meet the food needs of the population. On the other hand, the lowest EROI was observed in highly developed regions, where production ensures food self-sufficiency. However, the changes that have taken place in Europe since the 1990s indicate an opportunity to simultaneously reduce the direct use of energy in agriculture and increase the production of edible energy, thus improving the EROI.

Keywords: EROI; energy efficiency; edible energy; food production; direct energy use

1. Introduction

Since the end of World War II, the world's population has been growing steadily and the projections, by 2100, indicate that it will continue to grow [1]. In this context, the main function of agriculture is to feed the growing world population. In recent decades, the use of fertilizers, pesticides, improved water management and technological innovations have allowed increasing agricultural production [2]. The increase in agricultural productivity is associated with the high use of energy, including fossil fuel energy [3]. Agricultural intensification, starting with the Green Revolution, often has a negative impact on the environment [4,5]. Moreover, access to relatively cheap transport after World War II has contributed to the acceleration of the globalization process [6]. Both the intensification and globalization of production have contributed to the increased consumption of energy, mainly from fossil fuels, with regard to agriculture. From the global perspective, this proved to be a factor that negatively influenced the average energy efficiency of agricultural production [7].

According to many studies, global energy production will remain dependent on fossil fuels at least to 2050 [8]. Despite the constant decrease of net energy production from fossil



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). fuels due to the increasing energy input for its extraction [9], it is still higher than net energy production from renewable sources [10,11]. Brockway et al. [12] claimed that net energy production from fossil fuels is much lower than suggested by previous studies, which may in fact result in a faster-than-expected reduction in the amount of energy available to society. Currently applied agricultural production techniques are still strongly dependent on fossil fuels [13,14], which, concerning the aforementioned problems, increases the need to improve energy efficiency in this sector. Therefore, the need to improve the energy efficiency of agricultural production is related both to the projected population growth, which affects the increase in demand for food and the growing input required to obtain the energy necessary for the food production process.

The literature provides many approaches concerning the measurement of energy efficiency [15] but the most commonly used indicator is the energy return on investment (EROI). EROI can be defined as the relationship between total energy production and the energy used for this production [16]. This concept was first used in research on fish migration [17] and soon afterwards it was widely applied in energy systems analyses [18]. EROI was first used in research on the food production system by Pimentel et al. [19]. Concerning agriculture itself, EROI measures how much edible biomass energy is produced from the invested unit of energy [20]. According to the methodology adopted by the United Nations Food and Agriculture Organization (FAO), edible energy production refers to the energy suitable for human consumption, that is, the energy that can potentially be provided by food produced. A higher EROI value indicates higher energy efficiency in agricultural production. However, the occurrence of high values should not be considered optimal, as exceedingly high EROI might be accompanied by shortages in food production. In general, however, it is desirable for EROI to increase when the demand for food is met.

Concerning the analyses that use EROI to measure agricultural production, there are currently three main directions of research [21]. First, the studies compare the EROI of conventional agriculture to organic farming or other alternative production systems [22–24]. The conclusions of these studies usually indicate that the achievement of higher production in conventional systems is associated with providing higher energy input, as well as putting greater pressure on the environment. The second type of analysis involves focusing on the change of EROI concerning single agricultural products over time [25–28]. This research describes how to optimize energy use for individual agricultural products and thus improve their energy efficiency. The third type of analysis includes calculating the EROI of agriculture of the whole country over a long period [29–32]. These analyses show which areas of production are more energy-efficient and create the basis for optimization of production structures. Some studies have also taken into account the entire food production system [33–35]. They indicate the energy efficiency of individual phases of the food production chain [36].

In most cases, research concerning individual countries proves a decrease in the EROI of agriculture during the early industrialization of a given sector [37]. However, in recent decades, some countries have been able to significantly increase their EROI [3,38]. Research results concerning the EROI of individual countries have one major disadvantage: they are usually incomparable [39]. There are two reasons for this. First, there are methodological differences in determining the system (process) boundaries or conversion factors for individual products, as well as other detailed assumptions about how EROI is calculated. These differences result from specific research investigations and, consequently, different ways of allocating energy inputs and outputs [40]. Despite attempts to create a general computational framework that would allow comparisons to be made [41,42], the final results of EROI depend on the research context. Therefore, it is necessary to indicate precisely what is included in energy consumption and production for each individual analysis.

Secondly, the EROI calculations found in the literature are most often based on data sources of individual countries, which means that there is a lack of international research based on data that would ensure comparability of results between countries. To the best of our knowledge, there are only two publications that analyze this issue on a global scale, which are based on data from the FAO. Conforti and Giampietro [43] investigated the EROI of fossil energy use in crop production between 1990 and 1991 using a sample of 75 countries worldwide. The results indicated that developed countries are characterized by the lowest EROI, amounting from around 1 to 2; the exceptions were Canada and the United States, where EROI was higher than 2 and was similar to the EROI of developing countries. The highest EROI, usually between 15 and 30, was found in African countries. In turn, Pellegrini and Fernández [44] analyzed the EROI of global crop production from 1961 to 2014, based on 58 countries that produce 95% of global crops. The research showed that the highest consumption and production of energy was in the countries with the highest use of irrigation and their EROI decreased significantly during the analyzed period. The authors declared that between 1961 and 2014, the general EROI in the world was in the shape of a U curve, reaching an average of about 3 in the initial years and about 4 in the final years. The highest EROI was characteristic of Africa and the lowest for highly developed regions: Oceania, North America and Europe. However, the studies presented above have one basic disadvantage: they do not take into account animal production, so the analyses presented do not cover the whole area of edible energy production. Thus, in the literature, there is a research gap resulting from the lack of internationally comparable studies on the energy efficiency of agricultural production (crop and animal).

The inclusion of animal production is important due to existence of large differences between energy intensity of food product categories. According to research describing this issue, the energy efficiency of animal production in individual countries is significantly lower than that of crop production [35,45]. It is mainly caused by feed conversion inefficiencies and high energy demands of creating animal fat and muscles. Moreover, the animal production is characterized by much higher range of energy inputs per kilogram of food than crop production [14,46], which can increase the differences in the obtained EROI values depending on the production directions. Furthermore, there are significant differences in structure of food-related energy use around the world. For instance, nearly 50% of total food-related energy use in the United States is associated with animal production [47], while in the Netherlands it is around 35% [48]. Considering above it can be concluded, apart from the differences in the structure, that the energy consumption associated with animal production accounts for a significant share of total food-related energy use, therefore, it should not be omitted in EROI studies.

Hence, the aim of this article is to calculate the EROI of edible crop and animal production over a long period worldwide, as well as indicators characterizing the energy productivity of agriculture and the energy intensity of this production. On the input side, the direct consumption of energy from fossil fuels (such as coal, gasoline and oil) in agriculture and electricity is taken into account. This research is based on uniform, internationally comparable FAO data, which allows for the analysis of the EROI obtained among various regions of the world. The analysis covers all continents but due to the limitations of available data, the research period slightly differs (the data for the years 1970-2018 is provided by the FAO in energy units on a uniform, annual basis but there are some gaps. This is particularly visible in the case of data from the 1970s, which, for some large countries, is missing or some energy sources are not included. For example, the data concerning the direct consumption of energy from coal in Asia covers the period since 1986, although this kind of energy was used earlier in large quantities [49]. In consequence, research periods vary from continent to continent). The period included in the research concerning North America covers 1970–2018, Oceania 1974–2018, Africa 1977–2018, South America 1976–2018, Asia 1986–2018 and Europe 1992–2018.

The main and original contribution of this paper is the inclusion of animal production in the analysis and conducting a dynamic comparative analysis on a global scale. Such research has not been conducted so far, which we consider to be a serious research gap, as the share of animal production in edible energy production in some regions reaches even over 40%. In regions where this share was previously low, its dynamic growth can be observed, which is related to demographic changes and the evolution of consumption patterns. After the above introduction, the rest of the article is divided according to the following structure: Section 2 includes a description of the data used and the methodology applied. Section 3 presents the research results and discussion. Section 4 contains a summary of the analysis, including suggested directions for further research and policy recommendations.

2. Materials and Methods

The data used for the calculation of production and energy consumption were retrieved from the FAOSTAT database. The number of calories from edible agricultural production was calculated on the basis of FAO food balances using the method proposed by Sadowski and Baer-Nawrocka [50]:

$$EEP = \sum_{i=1}^{n} FS_i * P * SSC_i, \tag{1}$$

where *EEP* is edible energy production in agriculture (kcal/year), FS_i is the food supply of product *i* (kcal/person/year), *P* is the population and SSC_i is the self-sufficiency coefficient of product *i*. SSC_i is calculated according to the formula:

$$SSC_i = PQ_i / DSQ_i, \tag{2}$$

where PQ_i is the production quantity of product *i* (tonnes/year), DSQ_i is the domestic supply quantity of product *i* (tonnes/year).

The aim of introducing *SSC* to the formula is to include international trade and possible stocks from previous years. Thus, if the value of export of a given product was higher than the value of import, it increased the amount of produced edible energy calculated on the basis of the food supply value; if the import was higher, the amount of edible energy decreased as it did not result from domestic production. Therefore, the *SSC* balances the equation of production. The advantage of using the presented method based on FAO data is also the fact that the FAO food balances include fodder in the production quantity and subtract it from the domestic supply quantity. The result is that this quantity of energy is subtracted from all the energy obtained in agricultural production, avoiding double counting. Moreover, the above method was chosen because, unlike other methods, it allows the calculation of energy production directly from food balances, without using external datasets, which allows full comparability of the obtained results between continents. The full list of edible products considered in the study with corresponding FAO's item codes is included in the Table A1.

The edible agricultural production energy consumption included the direct consumption of fossil fuels in agriculture (gas-diesel oil, motor gasoline, natural gas, liquefied petroleum gas, fuel oil and coal) and electricity. Fuels used in fishing were also included in the calculation, as edible energy production also covers fishery products. EROI was calculated as the quotient of edible energy production in agriculture and direct energy use in agriculture:

$$Edible \ EROI = EEP/DEU, \tag{3}$$

where *DEU* is direct energy use in agriculture. As FAO stores the values of energy consumption in terajoules and energy production in kcal, the value of energy consumption has been converted into kcal by multiplying it by the 238,902,957.6.

The EROI values below 1 mean that more energy is consumed than produced in the production process. Values above 1 mean that more energy is produced than is consumed in the production process. In general, as indicated earlier, the higher the value of edible EROI, the better. However, whether a given level of food production is able to meet the needs of a population is important—if it is not and the EROI is high, then this situation should be considered unfavorable.

Since indirect energy consumption in agriculture (e.g., the use of energy for the production of fertilizers, pesticides or agricultural machinery) is an estimate calculated on the basis of many conversion factors that vary in the literature depending on the study and the country, as well as the assumptions made [3], it was not included in this edible EROI

calculation. To maintain comparability among the continents, the calculation includes only direct energy consumption, which corresponds to the first level of boundary for energy inputs according to standards proposed by Murphy et al. [39]. The impact of not considering indirect energy consumption is presented in the results and discussion section.

For both edible energy production in agriculture (*EEP*) and direct energy use in agriculture (*DEU*), three indicators were calculated, dividing both values by the number of inhabitants, the area of agricultural land and the value of agricultural edible production. For consistency the population data were retrieved from the FAO's food balances and area of agricultural land from the FAO's land use data. The value of agricultural edible production refers to the gross production value of food at constant 2014–2016 prices, which was also retrieved from FAO database.

The results were presented concerning given decades, taking into account the survey period for each continent. For example, the 2010s are represented by the 2010–2018 period and the 1970s are represented by different periods depending on the continent, which is related to the previously mentioned gaps in FAO data. For each indicator, the average growth rate (AGR) was also calculated as the geometric mean of chain indexes from all the years of the analyzed periods.

3. Results and Discussion

The calculations show that during the researched period, the highest EROI of the production of edible energy was visible in Africa, 24 on average. However, between 1977 and 2018, a decrease was found from about 57 in the first period to about 12 in the last (Table 1). The average growth rate of the indicator was -4%, which indicates similar transformations in energy efficiency in Africa to those that occurred in the rest of the world during agricultural mechanization and industrialization [37]. However, the lowest value of EROI in Africa was obtained in 2007, since than it started growing at a slow pace (Figure 1). The lowest EROI values could be observed in highly developed regions of the world, namely North America, Europe and Oceania, which is similar to the results of the previously discussed studies on the energy efficiency of crop production [43,44]. This may indicate a certain similarity of energy efficiency in case of animal and crop production within continents. The results are similar in the sense that the continents that had the highest or the lowest EROI in the crop production have it also in case of crop and animal production together. However, It does not mean that the values of these EROIs are the same, since they are not comparable. Concerning this study, it is vital to calculate only edible energy production. To do so, one must subtract the production of fodder from the value of agricultural production, as it constitutes a part of crop production but at the same time is also an input in animal production. On the other hand, the conversion factor of energy from crop products being fodder into energy from animal products always exceeds 1, as this is due to, among others, the living needs of animals and energy losses. The organism of an animal is not a perfect machine producing energy without losses from an energy source such as fodder.

North America and Oceania were characterized by EROI fluctuations during the research period, which is partly due to the high impact of individual countries on the final values of indicators. In the case of North America, this country is the United States and for Oceania, it is Australia. The amount of energy used in agriculture and the amount of edible energy produced can be significantly influenced by weather conditions. Such weather conditions are characterized by annual fluctuations in individual countries and can also yield fluctuations. According to the data provided by the FAO, fluctuations in cereal yields in the research period occurred both for the United States and Australia. The average EROI in North America during the research period was about 2.2 and its standard deviation was 0.26. In Oceania, on the other hand, the average EROI was 1.9, the lowest among the continents and its standard deviation was 0.27. For North America, our results differ from those presented by Conforti and Giampietro [43], who concluded that EROI in Canada and the US are closer to Asian countries than to other developed countries.

previously indicated, the results of these studies are not fully comparable to ours due to the different methodology.

Table 1. Standard deviation, average growth rate and average Edible energy return on investment (EROI) values for years 1970–2018.

Region	EROI in 1970s	EROI in 1980s	EROI in 1990s	EROI in 2000s	EROI in 2010s	Standard Deviation for Analyzed Period	Average Growth Rate (AGR) for Analyzed Period %
South America (1976–2018)	5.35	4.74	4.14	3.65	3.87	0.63	-0.68
North America (1970–2018)	2.32	1.86	2.30	2.16	2.29	0.26	0.07
Europe (1992–2018)	-	-	1.57	2.12	2.45	0.37	2.21
Asia (1986–2018)	-	5.85	4.86	4.88	4.61	0.41	-0.85
Africa (1977–2018)	57.25	40.49	17.55	12.56	11.78	15.71	-3.97
Oceania (1974–2018)	2.34	1.89	1.96	1.65	1.72	0.27	-1.19

Detailed average results used during the EROI calculations are presented in Table A2.



Figure 1. Energy return on investment (EdibleEROI) (kcal/kcal) (note logarithmic scale).

The opposite trend occurred concerning Europe, where at the beginning of the 1990s, the EROI hovered around 1.5; by the end of the research period, it significantly exceeded 2.4. The average growth rate in the years 1992–2018 was 2.2% and was, by far, the highest among the continents surveyed. The change toward higher energy efficiency in Europe was set by the European Union, which in 1993 adopted a law aimed at improving energy efficiency [51] and further reformed it in subsequent years [52,53].

In South America and Asia, the EROIs were on average higher than those in the most developed regions but, during the analyzed period, were characterized by a decrease and slight fluctuations. What is more, the average EROI for South America during the researched period was 4.25, with an average growth rate of -0.68%. In Asia, however, the

average EROI was about 4.9 and the average growth rate was -0.85%. These results in general are in line with studies conducted in individual countries [29,30,32]. However, the results are not so unambiguous in the case of individual products. For example, research results by Pracha and Volk [25] confirm the downward trend of the EROI for Pakistan's wheat but for rice production the EROI trend was more volatile. Similarly, results by Infante-Amate and Picado [27] indicate a downward trend in the energy efficiency of coffee production in Costa-Rica.

As it was mentioned before, the animal production is less energy efficient than crop production, thus, the obtained EROI results may be influenced by the share of animal production in edible production on individual continents. It should be assumed that higher share of animal production lowers average EROI values within continent. However, simple Pearson's correlation coefficients for EROI values and share of animal production in edible energy production do not confirm this as their values are relatively low (Table 2). On the other hand, one could argue that the highest share of animal production in edible energy production is observed in Oceania, which also has the lowest values of EROI. Moreover, opposite situation concerns Africa where the EROI values are the highest and the share of animal production in edible energy production is the lowest. However, there are long periods in which the EROI between continents was similar despite the differences in animal production shares in edible energy production, which is especially true for North America and Oceania until the late 1990s and to the lesser extend for Asia and South America during the analyzed period. It can be concluded that, although animal production is less energy-efficient than crop production, it does not mean that its higher shares result in the lack of ability to produce edible energy efficiently. In fact, the obtained results indicate that the development level of continents should be consider as the main driver of edible EROI values regardless of production direction (animal or crop). As it was mention before, the highest EROI values were observed in the least developed regions and the lowest values in the most developed regions in case of crop production alone [43,44] and as indicated by this study, in case of animal and crop production combined. The importance of economic development for the results of EROI is confirmed by Steinhart and Steinhart [54], who, based on the example of the United States, found that the relationship between energy consumption and food production has the shape of a logistic growth curve. Therefore, increases in food production due to increased energy inputs are higher in less developed regions.

Table 2. Share of animal production in edible energy production for years 1970–2018 and its co	orrelation coefficients with
EROI values.	

Region	1970s	1980s	1990s	2000s	2010s	Pearson's Correlation Coefficients with EROI Values for Analyzed Period
South America (1976–2018)	16.9	17.5	20.1	21.3	25.6	-0.38
North America (1970–2018)	24.3	23.2	22.1	23.2	23.4	-0.14
Europe (1992–2018)	-	-	30.3	28.7	25.8	-0.70
Asia (1986–2018)	-	9.2	12.2	14.2	15.2	-0.64
Africa (1977–2018)	7.3	7.2	7.0	7.7	11.3	-0.28
Oceania (1974–2018)	44.4	42.4	44.0	44.8	36.7	0.20

The literature analyses of the EROI of the agricultural sector showed that the wider the system boundaries, the lower the EROI. This is due to the fact that the increase in the amount of energy consumed resulted in increasing the value of the equation's denominator [55]. This fact should be taken into account when the results are analyzed. For example, the boundaries can be extended to include intermediate energy consumption in agricultural production. It is related to the use of fossil fuels for the production of fertilizers, pesticides or machinery. Many authors also classify other activities as intermediate consumption but the three mentioned in this study are commonly recognized and comprise the largest part of it [56]. If, for example, one were to consider the estimated results for intermediate consumption calculated by Arizpe et al. [57], the results of the Edible EROI would be, on average, lower for North America by 36%, from 2.25 to 1.65 in 1991. As Harchaoui and Chatzimpiros [3] pointed out, extending the system boundaries for the inclusion of other types of production, for example, food processing or household food processing, could result in a decrease of EROI below 1 in some countries. Concerning food, such a low rate may be acceptable because it must be produced regardless of the rationality of the process.

Moving to detailed indicators, the clear differences are apparent between the calculated indicators of edible energy production (Table 3) and energy consumption (Table 4) in particular decades in the researched regions. In the case of production indicators, their increase per capita (per consumer), signifying an increase in food security (food availability), as well as per hectare, indicating higher "energy productivity" of agricultural land, is desirable. In the case of edible energy production, the lower indicators show a higher unit production value. The higher the value of the production, shown in the denominator, the lower the indicator. From the point of view of a producer, it is a favorable situation, as they receive more money per unit of energy produced; such an interpretative approach was adopted when the indicator of edible energy production per value of the production was discussed.

Region	Edible Energy Production Indicator	Thousands kcal	1970s	1980s	1990s	2000s	2010s	AGR %
South	Per number of citizens Per agricultural area	kcal/person kcal/ha	992 498	1005 561	1034 694	1134 869	1261 1034	0.71 2.00
(1976–2018)	Per value of production	kcal/const. Int\$	2.08	2.03	1.93	1.72	1.61	-0.55
North	Per number of citizens Per agricultural area	kcal/person kcal/ha	1280 655	1379 801	1417 941	1435 1087	1459 1229	0.60 1.84
(1970–2018)	Per value of production	kcal/const. Int\$	1.62	1.68	1.69	1.64	1.57	-0.02
Europe (1992–2018)	Per number of citizens Per agricultural area	kcal/person kcal/ha	-	-	1148 1704	1192 1835	1218 1951	0.20 0.61
	Per value of production	kcal/const. Int\$	-	-	1.68	1.77	1.70	0.09
Asia	Per number of citizens Per agricultural area	kcal/person kcal/ha	-	844 1983	882 1915	917 2144	977 2543	0.53 1.02
(1986–2018)	Per value of production	kcal/const. Int\$	-	3.59	3.18	2.74	2.49	-1.21
Africa	Per number of citizens Per agricultural area	kcal/person kcal/ha	764 302	765 359	806 485	845 622	830 766	0.13 2.53
(1977–2018)	Per value of production	kcal/const. Int\$	3.17	3.27	3.15	3.00	2.72	-0.35
Oceania	Per number of citizens Per agricultural area	kcal/person kcal/ha	1660 60	1673 69	1697 83	1707 106	1769 142	-0.03 2.07
(1974–2018)	Per value of production	kcal/const. Int\$	0.97	1.00	0.97	0.92	0.96	-0.38

Table 3. Edible energy production in agriculture for years 1970–2018.

Constant Int\$ refers to the value of food production at constant 2014–2016 prices.

Region	Edible Energy Production Indicator	Thousands kcal	1970s	1980s	1990s	2000s	2010s	AGR %
South America (1976–2018)	Per number of citizens Per agricultural area	kcal/person kcal/ha	185 93	212 118	250 167	311 238	326 267	1.40 2.70
	Per value of production	kcal/const. Int\$	0.39	0.43	0.46	0.47	0.42	0.13
North America (1970–2018)	Per number of citizens Per agricultural area	kcal/person kcal/ha	553 283	742 431	616 409	664 503	636 536	0.53 1.77
	Per value of production	kcal/const. Int\$	0.70	0.91	0.74	0.76	0.68	-0.08
Europe	Per number of citizens	kcal/person	-	-	732	562	497	-1.96
	Per agricultural area	kcal/ha	-	-	1086	865	796	-1.57
(1992–2018)	Per value of production	kcal/const. Int\$	-	-	1.07	0.83	0.69	-2.07
	Per number of citizens	kcal/person	-	144	182	188	212	1.39
Asia	Per agricultural area	kcaĺ/ha	-	339	394	440	552	1.88
(1986–2018)	Per value of production	kcal/const. Int\$	-	0.61	0.65	0.56	0.54	-0.37
	Per number of citizens	kcal/person	13	19	46	67	71	4.27
Africa	Per agricultural area	kcal/ha	5	9	28	50	65	6.77
(1977–2018)	Per value of production	kcal/const. Int\$	0.06	0.08	0.18	0.24	0.23	3.77
	Per number of citizens	kcal/person	710	887	867	1034	1026	1.17
Oceania (1974–2018)	Per agricultural area	kcal/ha	26	37	43	64	82	3.30
	Per value of production	kcal/const. Int\$	0.42	0.53	0.50	0.56	0.55	0.82

 Table 4. Direct energy consumption in agriculture for years 1970–2018.

Constant Int\$ refers to the value of food production at constant 2014-2016 prices.

In the case of energy consumption indicators, the situation is slightly more complicated. Low values per hectare usually indicate low production intensity, which on the one hand can cause low productivity of the land but on the other hand, can result in a number of positive effects, for example, lower pressure on the environment. It could be considered from different perspectives, for example, whether the low energy inputs are the choice of a farmer or they resulting from the low level of economic development in the region, which forces farmers to produce with low energy inputs. Another factor influencing the energy input per 1 ha of agricultural land and per capita is population density, which is closely related to the area of agricultural land per 1 inhabitant. What is more, climatic and natural conditions (e.g., the share of permanent grassland, soil quality, length of vegetation period, level temperature, amount and distribution of precipitation) and the associated production structure, including the role of crop and animal production, also have an impact.

It is of key importance to shape the relationship between energy consumption and the production of edible energy as part of agricultural production. These relationships might be analyzed concerning both static and dynamic approaches. In the case of the indicator of energy consumption per unit of production value, lower values that prove better economic efficiency of the energy invested are desirable but the appropriate level of production still needs to be taken into account. Concerning a dynamic approach, it is desirable that energy input consumption grows slower than the value of agricultural production, assuming that production is sufficient to meet the needs of food consumers.

However, although in South America the EROI was decreasing until the last analyzed decade, that is, energy consumption was growing faster than its production, there was a clear increase in productivity per hectare (2% per year on average). Despite the rapid increase in energy production per hectare in South America, it is relatively low compared to the most developed regions (Europe and North America). Indicators per capita grew at a slower rate, which is due to the rapid growth of the South American population over the analyzed period. In contrast, it was shown that the indicator of energy production per capita in the analyzed region has been, in recent years, higher to that achieved in Europe, which illustrates an improvement in food self-sufficiency in South America. The

high level of self-sufficiency observed in recent years can also be confirmed by other research [58]. At the same time, the direct energy consumption needed to produce one Int\$ remained relatively stable in the analyzed period (AGR was 0.13%); however, the amount of edible energy produced per Int\$ (as evidence by a -0.55% decrease in AGR) increased significantly. This might be considered a favorable situation from the point of view of agricultural producers, as the unit value of production increased, while the economic efficiency of the energy invested remained relatively stable.

The observed fluctuations of EROI in North America are reflected in the analyzed direct energy consumption indicators, which generally grew, yet fluctuated. Energy consumption per hectare of agricultural land increased particularly rapidly, indicating a progressive, energy-intensive escalation of production (1.77%) and it increased more moderately per capita (0.53%). Production expressed in energy per hectare and per capita, respectively (1.84% and 0.60%), increased at a slightly faster rate than the increase in energy input, resulting in a visible improvement in productivity. In the 1990s, when EROI was higher than in following decades, there was a decrease in direct energy consumption; this is also reflected by indicators per capita and per hectare of agricultural land. Moreover, the indicators of energy consumption and production per value of production were directly proportional; the exception occurred in the 1990s, when there was an increase in the economic efficiency of energy consumption. At the same time, North America is characterized by a relatively high individual value of edible energy production and low economic efficiency of energy consumption in agriculture. Other research that takes North American countries into account illustrates the occurrence of fluctuations concerning direct fuel consumption in agriculture [59] and points out the increase in energy efficiency in the 1990s, claiming it was due to the change in production direction toward more energy-efficient agriculture [38].

In examining Europe, the increase in EROI is evident, as well as in energy production per hectare and per capita in the analyzed period (with relatively high values of their indicators), in the years 1992-2018. However, the EROI increase was mainly due to a decrease in direct energy consumption in agriculture. Moreover, the energy intensity of production visibly decreased, which is reflected by a decrease in energy consumption per hectare and per capita. Together with increases in production rates, this provided the fastest change toward more energy-efficient edible production compared to other continents. The only indicator that deteriorated slightly was the decrease in the individual value of energy production, reflected by the average increase of production required to obtain the value of one Int\$. However, its values were relatively stable in analyzed period. At the same time, in the 1990s, a decrease was found in the direct energy consumption required to produce one Int\$ worth of edible energy, which was still the highest among the regions subject to analysis. As indicated by other studies [44], in Europe, before the 1990s, the EROI was decreasing as a result of rapidly increasing energy use in agriculture, even though steady growth in production was maintained. In the 1990s, energy consumption began to decrease while production growth remained steady, resulting in obvious improvements in energy efficiency.

During the analyzed period, direct energy consumption per hectare as well as per capita in Asia grew at faster rate than edible energy production. However, due to high population density and significant population growth in recent decades, Asia has relatively low edible energy production per person, resulting in food availability problems in this region. At the same time, Asia had the highest edible energy production per hectare of agricultural land in the world. This is mainly influenced by the low ratio of area of agricultural land per 1 inhabitant, which makes it necessary to obtain high production from 1 ha of agricultural land and in many regions to yield two or even three crops in one year. High production from 1 ha is also optimal due to the structure of agriculture (many small farms). During the analyzed period, the individual value of edible energy production in Asia increased and the economic efficiency of energy consumption in agriculture improved. This might be reflected by the decrease of the energy use and energy production per value

of production (AGR was -0.37% and -1.21%, respectively), which were relatively high at the beginning of the considered period.

In Africa, the rapid EROI decrease until 2007 was mainly due to an increase in direct energy consumption in order to increase production. Energy consumption per person increased sixfold, while per hectare increased more than fourteenfold in the whole analyzed period but the values remained relatively low. What is more, although there was a desirable increase in edible energy production, it was insufficient to guarantee food availability in Africa [60,61]. As mentioned earlier, similar changes to those occurring in Africa were found during the period under consideration, after the industrial revolution on other continents as well; however, now, with the EROI of fossil fuel decreasing, reliance on fossil fuel-based energy production might have a negative impact on its increase in the long term [62]. The rising Africa's edible EROI since 2008 was due to lower increase in energy consumption and simultaneous growth in energy production, however, in the last decade (2010–2018) the decrease in energy production per person can be observed. An increase in EROI in the absence of food self-sufficiency and a decrease in edible energy production per capita in 2010–2018, should be considered as unfavorable. The individual value of edible energy production in the analyzed period also increased, with a simultaneous decrease in economic efficiency from the energy invested. However, it remained high only due to unsatisfactory energy use, which resulted in insufficient production. In this context, the decrease concerning the discussed energy efficiency of production should not be considered something negative.

Unlike the other analyzed regions, Oceania had several times lower energy use and production per hectare of agricultural land than per person. The results concerning Oceania are mainly derived from the results of Australia and, to a lesser extent, New Zealand, countries that are characterized by extensive agricultural production on a large area of agricultural land. The structure of agricultural land is dominated by permanent grasslands (permanent meadows and pastures). During the analyzed period, their share in Australia exceeded 90% and in New Zealand 95%. A large number of areas of agricultural land per 1 inhabitant ensures that Oceania also has the highest rate of edible energy production per person but much of this production is exported. The direct energy consumption per capita is high because an increase in energy consumption ensures an increase in production, as it is less efficient concerning energy use. The individual value of edible production expressed in kcal per Int\$ remained more or less constant over the analyzed period, while the economic efficiency of energy use in agriculture declined to some extent, as a result of the increasing size of cattle production in Oceania.

4. Conclusions and Policy Recommendations

The study on edible energy production and its direct consumption in agriculture determined that the highest edible EROI is present in Africa and the lowest in the most developed regions. During the analyzed period, energy consumption in agriculture worldwide increased, contributing to the increase of edible energy production. The only exception was Europe, where, since the 1990s, a decrease was found in direct energy use, mainly concerning energy from fossil fuels, while an increase in energy production was found, resulting in a visible improvement of edible EROI. The changes that took place in Europe, mainly due to the Common Agricultural Policy of the European Union, confirm the possibility of improving the energy efficiency of crop and animal production while reducing the use of fossil fuels, which is particularly important considering the decreasing energy efficiency of their extraction and expectations concerning the reduction of pollution generation while meeting growing food needs.

The analysis broadened the scope of the international comparison of EROI in agriculture present in the literature, including animal production. This proves that in regions with low or high EROI for crop production, correspondingly low or high EROI can be found for animal and crop production combined. This indicates that the regions' ability to effectively convert energy into edible energy does not depend solely on the direction of production (animal or crop). However, it must be remembered that the energy efficiency of animal production is, in fact, significantly lower than that of crop production.

The presented results of EROI should be interpreted only within the scope of the established system boundaries, that is, it is a study on the relationship between edible energy production from agriculture and the direct use of fossil fuels and electricity in agriculture; this constitutes a limitation to the conducted studies. When carrying out the analysis, we tried to avoid using conversion factors for production or energy consumption, which could be based on different sources, so the study included only the factors used by the FAO; however, this limited the scope of the system boundaries. On the one hand, this is the limitation of this article but on the other hand, it also sets out future research directions that could focus on extending the system boundaries using methodologically uniform conversion factors for indirect energy consumption, including animal and crop production in research. Extending the system boundaries in research is undoubtedly a vital issue from the point of view of assessing the energy efficiency of agricultural production, as indirect energy consumption associated with the use of fertilizers, pesticides, irrigation systems and possibly agricultural machinery comprises one of the key inputs; at the same time, significant improvement concerning this matter is possible.

Another direction of further research includes incorporating links of the food supply chain in the analysis. Although agriculture is the most energy-intensive phase of the food chain, other phases such as food processing, logistics, packaging and food waste are also crucial for energy efficiency improvement opportunities.

Finally, a key extension of our research would be the analysis of drivers of global changes in energy efficiency in agricultural production. A review of the literature and research conducted in individual countries suggests that the most important drivers include changes in the structure of food consumption and production, applied technologies and practices in agriculture, climate change, and, perhaps most importantly, policy for energy use in agriculture and food production. However, determining the exact impact of individual factors on the efficiency of global edible energy production requires more detailed analysis and is challenging in terms of obtaining comparable data.

Nevertheless, based on the research results and the literature review, some concluding policy recommendations can be formulated. The example of Europe, in which it was possible to simultaneously improve the energy efficiency of agricultural production and reduce the use of fossil fuels, suggests that the state policy has a key direct impact (instruments supporting the use of alternative energy sources) and indirect impact (instruments supporting the implementation of new technologies and practices in agriculture, stimulating a change in consumption and production structure) on energy efficiency. The EU's Common Agricultural Policy has played a special role by encouraging investment in more sustainable farming methods. The same can be said about rural development programs, which aim to facilitate the supply and use of renewable energy sources. Therefore, drawing on the EU's experience in reducing direct consumption of fossil energy and electricity in agriculture, the following tools should be introduced: (i) measures promoting and supporting the production and use of renewable energy sources such as biofuels, wind energy, solar energy and hydropower systems; (ii) incentives for changing the structure of food consumption and production toward limiting the consumption of meat and switching to the consumption of local and seasonal products; (iii) measures promoting and supporting conservation agriculture and organic farming; and (iv) support for R&D and implementation of innovative farming techniques, such as precision agriculture or irrigation technologies.

It is worth emphasizing that the above policy recommendations, formulated on the basis of experience and success in the field of improving the energy efficiency of agricultural production in European countries, apply mainly to developed countries, although to a certain extent and subject to regional modification, they should also be applied in less developed countries because the separation of agriculture productivity from energy consumption remains a challenge across the globe. **Author Contributions:** Conceptualization, B.B.; methodology, B.B.; validation, A.P.-W. and W.P.; formal analysis, B.B. and J.Ł.; investigation, B.B.; data curation, B.B. and J.Ł.; writing—original draft preparation, B.B. and J.Ł.; writing—review and editing, A.P.-W. and W.P.; visualization, B.B. and J.Ł.; supervision, W.P. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Table A1. The list of products that have been considered for edible energy production with their corresponding FAO's item code.

FAO's Item Code	Name	FAO's Item Code	Name	FAO's Item Code	Name
2656	Beer	2619	Dates	2645	Spices, Other
2658	Beverages, Alcoholic	2625	Fruits, Other	2532	Cassava and
2657	Beverages, Fermented	2613	Grapefruit and products	2531	Potatoes and products
2655	Wine	2620	Grapes and products	2534	Roots, Other
2740	Butter, Ghee	2612	Lemons, Limes and products	2533	Sweet potatoes
2743	Cream	2611	Oranges, Mandarines	2535	Yams
2737	Fats, Animals, Raw	2618	Pineapples and products	2633	Cocoa Beans and
2781 2782	Fish, Body Oil Fish, Liver Oil	2616 2731	Plantains Bovine Meat	2630 2635	Coffee and products Tea (including mate)
2769	Aquatic Animals, Others	2735	Meat, Other	2745	Honey
2775	Aquatic Plants	2732	Mutton & Goat Meat	2542	Sugar (Raw Equivalent)
2768	Meat, Aquatic Mammals	2733	Pigmeat	2541	⁻ Sugar non-centrifugal
2513	Barley and products	2734	Poultry Meat	2543	Sweeteners, Other
2520	Cereals, Other	2848	Butter	2537	Sugar beet
2514	Maize and products	2680	Infant food	2536	Sugar cane
2517	Millet and products Oats	2899	Offals, Edible	2551 2578	Nuts and products Coconut Oil
2805	Rice and products	2560	Coconuts—Incl Copra	2575	Cottonseed Oil
2515	Rye and products	2556	Groundnuts (Shelled Eq)	2572	Groundnut Oil
2518	Sorghum and products	2570	Oilcrops, Other	2582	Maize Germ Oil
2511	Wheat and products	2563	Olives (including	2586	Oilcrops Oil, Other
2744	Eggs	2562	Palm kernels	2580	Olive Oil
2766	Cephalopods	2558	Rape and Mustardaged	2577	Palm Oil
2765	Crustaceans	2561	Sesame seed	2576	Palmkernel Oil
2762	Demersal Fish	2555	Soyabeans	2574	Rape and Mustard
2761 2764 2767	Freshwater Fish Marine Fish, Other Molluscs, Other	2557 2546 2547	Sunflower seed Beans Peas	2581 2579 2571	Ricebran Oil Sesameseed Oil Soyabean Oil
2763	Pelagic Fish	2549	Pulses, Other and	2573	Sunflowerseed Oil
2617	Apples and products	2642	Cloves	2602	Onions
2615	Bananas	2640	Pepper	2601	Tomatoes and products
2614	Citrus, Other	2641	Pimento	2605	Vegetables, Other

Region	Indicator	Unit	1970s	1980s	1990s	2000s	2010s
	Food supply (FS) Population (P)	Thousands Millions	940.3 274.2	949.0 318.8	972.2 382.9	1033.6 443.3	1094.5 492.5
South America (1976–2018)	Self-sufficiency coefficient (SSC)	-	1.06	1.06	1.06	1.10	1.15
	Edible energy production (EEP)	Trillions	272.1	320.5	396.1	502.9	621.2
	Direct energy use (DEU)	Trillions	50.8	67.7	95.6	137.9	160.6
	Food supply (FS) Population (P)	Thousands Millions	1095.7 302.5	1179.9 343.9	1249.7 390.7	1301.0 439.3	1291.4 477.5
North America	Self-sufficiency coefficient (SSC)	-	1.17	1.17	1.13	1.10	1.13
(1970–2018)	Edible energy production (<i>EEP</i>)	Trillions	387.2	474.2	553.6	630.4	696.7
	Direct energy use (DEU)	Trillions	167.2	255.3	240.6	291.7	303.7
	Food supply (FS) Population (P)	Thousands Millions		- -	1165.1 728.6	1210.2 732.8	1230.7 743.7
Europe (1992–2018)	Self-sufficiency coefficient (SSC) Edible energy production (EEP)	-	-	-	0.99	0.99	0.99
(1772 2010)		Trillions	-	-	836.5	873.8	906.0
	Direct energy use (DEU)	Trillions	-	-	533.0	411.9	369.5
	Food supply (FS) Population (P)	Thousands Millions	-	874.2 2977.4	911.7 3416.3	956.1 3891.2	1019.6 4330.6
Asia (1986–2018)	Self-sufficiency coefficient (SSC) Edible energy production (EEP)	-	-	0.96	0.97	0.96	0.96
(1900-2010)		Trillions	-	2511.6	3013.2	3566.6	4231.0
	Direct energy use (DEU)	Trillions	-	429.6	620.4	731.6	918.8
	Food supply (FS) Population (P)	Thousands Millions	792.6 417.4	818.8 501.3	864.6 646.9	917.3 819.7	951.8 1031.5
Africa (1977–2018)	Self-sufficiency coefficient (SSC) Edible energy production (EEP)	-	0.96	0.93	0.93	0.92	0.97
(1)// _010)		Trillions	318.7	383.4	521.4	692.6	949.8
	Direct energy use (DEU)	Trillions	5.6	9.5	29.7	55.1	72.7
	Food supply (FS) Population (P)	Thousands Millions	1104.2 18.6	1111.8 20.6	1116.0 23.6	1129.3 26.8	1200.9 30.8
Oceania (1974–2018)	Self-sufficiency coefficient (SSC)	-	1.50	1.51	1.52	1.51	1.47
(1771 2010)	Edible energy production (<i>EEP</i>)	Trillions	30.9	34.5	40.1	45.8	54.4
	Direct energy use (DEU)	Trillions	13.2	18.3	20.5	27.7	31.6

Table A2. Detailed average results used during the EROI calculations for years 1970–2018.

References

- 1. United Nations (UN). World population prospects 2019. Available online: https://population.un.org/wpp/DataQuery (accessed on 5 November 2020).
- 2. Mueller, N.D.; Gerber, J.S.; Johnston, M.; Ray, D.K.; Ramankutty, N.; Foley, J.A. Closing yield gaps through nutrient and water management. *Nat. Cell Biol.* 2012, 490, 254–257. [CrossRef] [PubMed]
- Harchaoui, S.; Chatzimpiros, P. Energy, Nitrogen, and Farm Surplus Transitions in Agriculture from Historical Data Modeling. France, 1882–2013. J. Ind. Ecol. 2019, 23, 412–425. [CrossRef]
- 4. Pimentel, D. Environmental and Economic Costs of the Application of Pesticides Primarily in the United States. *Environ. Dev. Sustain.* **2005**, *7*, 229–252. [CrossRef]
- Krausmann, F.; Erb, K.-H.; Gingrich, S.; Haberl, H.; Bondeau, A.; Gaube, V.; Lauk, C.; Plutzar, C.; Searchinger, T.D. Global human appropriation of net primary production doubled in the 20th century. *Proc. Natl. Acad. Sci.* 2013, 110, 10324–10329. [CrossRef] [PubMed]
- 6. Kastner, T.; Kastner, M.; Nonhebel, S. Tracing distant environmental impacts of agricultural products from a consumer perspective. *Ecol. Econ.* **2011**, *70*, 1032–1040. [CrossRef]
- 7. Parcerisas, L.; Dupras, J. From mixed farming to intensive agriculture: Energy profiles of agriculture in Quebec, Canada, 1871–2011. *Reg. Environ. Chang.* **2018**, *18*, 1047–1057. [CrossRef]

- Edenhofer, O.; Pichs-Madruga, R.; Sokona, Y.; Minx, J.C.; Farahani, C.; Kadner, S.; Seyboth, K.; Adler, A.; Baum, I.; Brunner, S.; et al. Climate change 2014: Mitigation of Climate Change. In *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: New York, NY, USA, 2014.
- Gagnon, N.; Hall, C.A.; Brinker, L. A Preliminary Investigation of Energy Return on Energy Investment for Global Oil and Gas Production. *Energies* 2009, 2, 490–503. [CrossRef]
- Hall, C.A.; Lambert, J.G.; Balogh, S.B. EROI of different fuels and the implications for society. *Energy Policy* 2014, 64, 141–152. [CrossRef]
- 11. King, L.C.; Bergh, J.C.J.M.V.D. Implications of net energy-return-on-investment for a low-carbon energy transition. *Nat. Energy* **2018**, *3*, 334–340. [CrossRef]
- 12. Brockway, P.E.; Owen, A.; Brand-Correa, L.I.; Hardt, L. Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. *Nat. Energy* **2019**, *4*, 612–621. [CrossRef]
- 13. Cruse, M.J.; Liebman, M.; Raman, D.R.; Wiedenhoeft, M.H. Fossil Energy Use in Conventional and Low-External-Input Cropping Systems. *Agron. J.* 2010, *102*, 934–941. [CrossRef]
- 14. Woods, J.; Williams, A.; Hughes, J.K.; Black, M.; Murphy, R. Energy and the food system. *Philos. Trans. R. Soc. B: Biol. Sci.* 2010, 365, 2991–3006. [CrossRef] [PubMed]
- 15. Mulder, K.; Hagens, N.J. Energy Return on Investment: Toward a Consistent Framework. Ambio 2008, 37, 74–79. [CrossRef]
- Kunz, H.; Hagens, N.J.; Balogh, S.B. The Influence of Output Variability from Renewable Electricity Generation on Net Energy Calculations. *Energies* 2014, 7, 150–172. [CrossRef]
- 17. Hall, C.A.S. Migration and Metabolism in a Temperate Stream Ecosystem. Ecology 1972, 53, 585–604. [CrossRef]
- 18. Court, V.; Fizaine, F. Long-Term Estimates of the Energy-Return-on-Investment (EROI) of Coal, Oil, and Gas Global Productions. *Ecol. Econ.* **2017**, *138*, 145–159. [CrossRef]
- 19. Pimentel, D.; Hurd, L.E.; Bellotti, A.C.; Forster, M.J.; Oka, I.N.; Sholes, O.D.; Whitman, R.J. Food Production and the Energy Crisis. *Science* **1973**, *182*, 443–449. [CrossRef]
- Guzmán, G.I.; De Molina, M.G. Energy Efficiency in Agrarian Systems From an Agroecological Perspective. *Agroecol. Sustain.* Food Syst. 2015, 39, 924–952. [CrossRef]
- Gingrich, S.; Marco, I.; Aguilera, E.; Padró, R.; Cattaneo, C.; Cunfer, G.; Guzmán, G.I.; MacFadyen, J.; Watson, A. Agroecosystem energy transitions in the old and new worlds: Trajectories and determinants at the regional scale. *Reg. Environ. Chang.* 2018, 18, 1089–1101. [CrossRef]
- 22. Atlason, R.S.; Kjaerheim, K.M.; Davidsdottir, B.; Ragnarsdottir, K.V. A Comparative Analysis of the Energy Return on Investment of Organic and Conventional Icelandic Dairy Farms. *Icel. Agric. Sci.* 2015, 28, 29–42. [CrossRef]
- Jónsson, J.; Örvar, G.; Davíðsdóttir, B.; Nikolaidis, N.P.; Giannakis, G.V. Tools for Sustainable Soil Management: Soil Ecosystem Services, EROI and Economic Analysis. *Ecol. Econ.* 2019, 157, 109–119. [CrossRef]
- 24. Pérez-Neira, D.; Schneider, M.; Armengot, L. Crop-diversification and organic management increase the energy efficiency of cacao plantations. *Agric. Syst.* 2020, 177, 102711. [CrossRef]
- 25. Pracha, A.S.; Volk, T.A. An Edible Energy Return on Investment (EEROI) Analysis of Wheat and Rice in Pakistan. *Sustainability* **2011**, *3*, 2358–2391. [CrossRef]
- Pittelkow, C.M.; Zorrilla, G.; Terra, J.; Riccetto, S.; Macedo, I.; Bonilla, C.; Roel, A. Sustainability of rice intensification in Uruguay from 1993 to 2013. *Glob. Food Secur.* 2016, *9*, 10–18. [CrossRef]
- 27. Infante-Amate, J.; Picado, W. Energy flows in the coffee plantations of Costa Rica: From traditional to modern systems (1935–2010). *Reg. Environ. Chang.* **2018**, *18*, 1059–1071. [CrossRef]
- Macedo, I.; Terra, J.A.; Siri-Prieto, G.; Velazco, J.I.; Carrasco-Letelier, L. Rice-pasture agroecosystem intensification affects energy use efficiency. J. Clean. Prod. 2021, 278, 123771. [CrossRef]
- 29. Ozkan, B.; Akcaoz, H.; Fert, C. Energy input-output analysis in Turkish agriculture. Renew. Energy 2004, 29, 39-51. [CrossRef]
- Cao, S.; Xie, G.; Zhen, L. Total embodied energy requirements and its decomposition in China's agricultural sector. *Ecol. Econ.* 2010, 69, 1396–1404. [CrossRef]
- 31. Veiga, J.P.S.; Romanelli, T.L.; Gimenez, L.M.; Busato, P.; Milan, M. Energy embodiment in Brazilian agriculture: An overview of 23 crops. *Sci. Agricola* **2015**, *72*, 471–477. [CrossRef]
- Guzmán, G.I.; De Molina, M.G.; Fernández, D.S.; Infante-Amate, J.; Aguilera, E. Spanish agriculture from 1900 to 2008: A long-term perspective on agroecosystem energy from an agroecological approach. *Reg. Environ. Chang.* 2018, 18, 995–1008. [CrossRef]
- Markussen, M.V.; Østergård, H. Energy Analysis of the Danish Food Production System: Food-EROI and Fossil Fuel Dependency. Energies 2013, 6, 4170–4186. [CrossRef]
- Galán, E.; Padró, R.; Marco, I.; Tello, E.; Cunfer, G.; Guzmán, G.; De Molina, M.G.; Krausmann, F.; Gingrich, S.; Sacristán, V.; et al. Widening the analysis of Energy Return on Investment (EROI) in agro-ecosystems: Socio-ecological transitions to industrialized farm systems (the Vallès County, Catalonia, c.1860 and 1999). *Ecol. Model.* 2016, 336, 13–25. [CrossRef]
- Laso, J.; Hoehn, D.; Margallo, M.; García-Herrero, I.; Batlle-Bayer, L.; Bala, A.; Fullana-I-Palmer, P.; Vázquez-Rowe, I.; Irabien, A.; Aldaco, R. Assessing Energy and Environmental Efficiency of the Spanish Agri-Food System Using the LCA/DEA Methodology. *Energies* 2018, 11, 3395. [CrossRef]

- 36. Bajan, B.; Mrówczyńska-Kamińska, A.; Poczta, W. Economic Energy Efficiency of Food Production Systems. *Energies* **2020**, *13*, 5826. [CrossRef]
- 37. Martinez-Alier, J. The EROI of agriculture and its use by the Via Campesina. J. Peasant. Stud. 2011, 38, 145–160. [CrossRef]
- 38. Hamilton, A.; Balogh, S.B.; Maxwell, A.; Hall, C.A.S. Efficiency of Edible Agriculture in Canada and the U.S. Over the Past Three and Four Decades. *Energies* **2013**, *6*, 1764–1793. [CrossRef]
- Murphy, D.J.; Hall, C.A.; Dale, M.; Cleveland, C.J. Order from Chaos: A Preliminary Protocol for Determining the EROI of Fuels. Sustainability 2011, 3, 1888–1907. [CrossRef]
- 40. Hall, C.A.; Dale, B.E.; Pimentel, D. Seeking to Understand the Reasons for Different Energy Return on Investment (EROI) Estimates for Biofuels. *Sustainability* **2011**, *3*, 2413–2432. [CrossRef]
- 41. Brandt, A.R.; Dale, M. A General Mathematical Framework for Calculating Systems-Scale Efficiency of Energy Extraction and Conversion: Energy Return on Investment (EROI) and Other Energy Return Ratios. *Energies* **2011**, *4*, 1211–1245. [CrossRef]
- Atlason, R.S.; Unnthorsson, R. Ideal EROI (energy return on investment) deepens the understanding of energy systems. *Energy* 2014, 67, 241–245. [CrossRef]
- 43. Conforti, P.; Giampietro, M. Fossil energy use in agriculture: An international comparison. *Agric. Ecosyst. Environ.* **1997**, *65*, 231–243. [CrossRef]
- 44. Pellegrini, P.; Fernández, R.J. Crop intensification, land use, and on-farm energy-use efficiency during the worldwide spread of the green revolution. *Proc. Natl. Acad. Sci.* 2018, *115*, 2335–2340. [CrossRef] [PubMed]
- 45. Pelletier, N.; Audsley, E.; Brodt, S.; Garnett, T.; Henriksson, P.J.G.; Kendall, A.; Kramer, K.J.; Murphy, D.; Nemecek, T.; Troell, M. Energy Intensity of Agriculture and Food Systems. *Annu. Rev. Environ. Resour.* **2011**, *36*, 223–246. [CrossRef]
- 46. Carlsson-Kanyama, A.; Ekström, M.P.; Shanahan, H. Food and life cycle energy inputs: Consequences of diet and ways to increase efficiency. *Ecol. Econ.* 2003, 44, 293–307. [CrossRef]
- 47. Pimentel, D.; Williamson, S.; Alexander, C.E.; Gonzalez-Pagan, O.; Kontak, C.; Mulkey, S.E. Reducing Energy Inputs in the US Food System. *Hum. Ecol.* 2008, *36*, 459–471. [CrossRef]
- 48. Gerbens-Leenes, P.; Nonhebel, S.; Ivens, W.; Gerbens-Leenes, W. A method to determine land requirements relating to food consumption patterns. *Agric. Ecosyst. Environ.* **2002**, *90*, 47–58. [CrossRef]
- 49. Siddiqi, T.A. Coal in Asia and the Pacific: A regional overview. Energy 1986, 11, 1049–1055. [CrossRef]
- 50. Sadowski, A.; Baer-Nawrocka, A. Food and environmental function in world agriculture—Interdependence or competition? *Land Use Policy* **2018**, *71*, 578–583. [CrossRef]
- 51. Council Directive 93/76/EEC of 13 September 1993 to Limit Carbon Dioxide Emissions by Improving Energy Efficiency. Available online: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A31993L0076 (accessed on 10 February 2021).
- 52. Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on Energy End-Use Efficiency and Energy Services and Repealing Council Directive 93/76/EEC. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/ ?uri=CELEX%3A32006L0032 (accessed on 10 February 2021).
- Directive, E.E. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32. *Off. J.* 2012, 315, 1–56.
 Steinhart, J.S.; Steinhart, C.E. Energy use in the US food system. *Science* 1974, *184*, 307–316.
- 55. Pelletier, N. Environmental performance in the US broiler poultry sector: Life cycle energy use and greenhouse gas, ozone depleting, acidifying and eutrophying emissions. *Agric. Syst.* **2008**, *98*, 67–73. [CrossRef]
- 56. Franzese, P.P.; Rydberg, T.; Russo, G.F.; Ulgiati, S. Sustainable biomass production: A comparison between Gross Energy Requirement and Emergy Synthesis methods. *Ecol. Indic.* **2009**, *9*, 959–970. [CrossRef]
- 57. Arizpe, N.; Giampietro, M.; Ramos-Martin, J. Food Security and Fossil Energy Dependence: An International Comparison of the Use of Fossil Energy in Agriculture (1991-2003). *Crit. Rev. Plant Sci.* **2011**, *30*, 45–63. [CrossRef]
- 58. Baer-Nawrocka, A.; Sadowski, A. Food security and food self-sufficiency around the world: A typology of countries. *PLOS ONE* **2019**, *14*, e0213448. [CrossRef] [PubMed]
- Cleveland, C. The direct and indirect use of fossil fuels and electricity in USA agriculture, 1910–1990. *Agric. Ecosyst. Environ.* 1995, 55, 111–121. [CrossRef]
- 60. Chakona, G.; Shackleton, C.M. Voices of the hungry: A qualitative measure of household food access and food insecurity in South Africa. *Agric. Food Secur.* 2017, *6*, 1–17. [CrossRef]
- Fraval, S.; Hammond, J.; Bogard, J.R.; Ng'Endo, M.; Van Etten, J.; Herrero, M.; Oosting, S.J.; De Boer, I.J.M.; Lannerstad, M.; Teufel, N.; et al. Food Access Deficiencies in Sub-saharan Africa: Prevalence and Implications for Agricultural Interventions. *Front. Sustain. Food Syst.* 2019, *3*, 104. [CrossRef]
- 62. Court, V.; Lantz, F.; Jouvet, P.-A. Long-term endogenous economic growth and energy transitions. *Energy J.* **2018**, *39*, 29–57. [CrossRef]