Food and Energy in the Global Sustainable Energy Transition: An Energy Metabolism View of Global Agriculture Systems

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Abstract:

We develop an energy input-output model that allows us to quantify the energy return on energy invested for food production on a global, as well on a regional scale and propose a quantitative framework that integrates food production and consumption into the transition path leading to a sustainable, renewable-energy driven economy. We conduct an energetic analysis of food energy flows and find that food despite the increase in production efficiency over the past half century, energetic efficiency has not improved. Therefore, with a prospect of an increasing population, we underline need of integrating the food energy system into future energy-economy decisions.

One Sentence Summary:

The incorporation of the food energy flows into the global energy system is a key component of a successful transition to a sustainable, renewable energy-driven economy.

Main Text

Introduction

Food and agriculture form an essential component of the energy metabolism of human societies that is invariably missing in reviews of global primary and final energy supply. When the caloric energy content of food is included as in Fig. 1 we see that it represented more than 5% (6.2% including biofuels, and 14.6% including biofuels and biomass from agriculture) of the total final energy supply (TFES) in 2010.

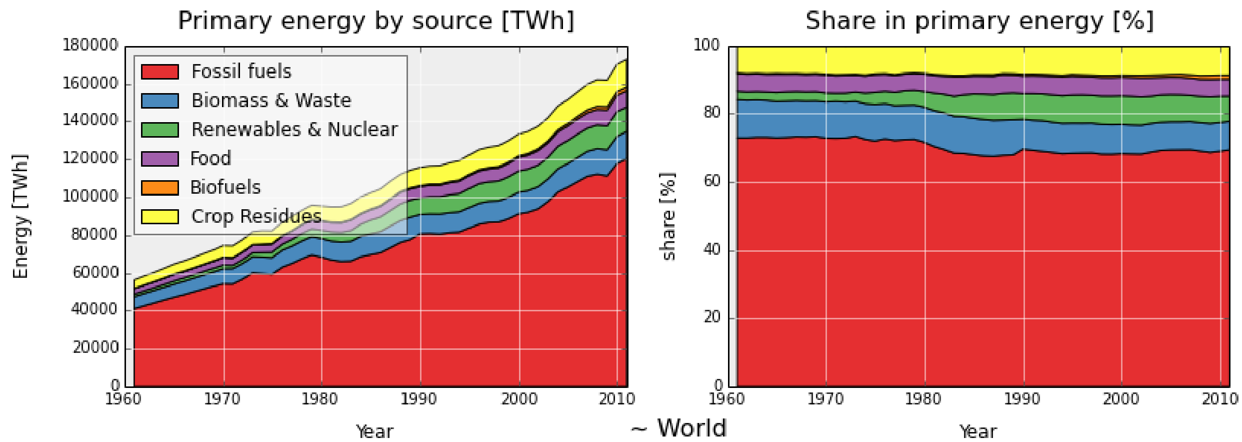


Fig. 1. Final Food Energy (Crop Residues (Agricultural Biomass) and Biofuels shown separately) In Comparison with Total Final Energy Supply (TFES).

In the decades since the Green Revolution, the rate of increase in food production significantly exceeded population growth despite reductions in agricultural land (Godfray et al. 2010) . Such intensification was the result of mechanization, irrigation, artificial fertilization, and pesticide protection (XXX) along with selective breeding and more recently genetic modification all of which depend on high energy (and material) intensity inputs.

The first oil crisis sparked concerns around the energy use in agriculture (Steinhart and Steinhart 1974; Pimentel et al. 1973)and warnings were issued on the difficulty to export energy intensive agriculture globally. Hirst's (1974) input-output model is still one of the most comprehensive energy-oriented studies of the global food system up to date, with more detailed case studies existing for the UK (Leach 1975) and in a more recent work for Sweden (Carlsson-Kanyama, Ekström, and Shanahan 2003). The Limits to Growth also modeled the interrelationship between the industrial system and food production in a global system(Donella H. Meadows et al. 1972). Easing of fossil fuel availability in the decades that followed though, permitted a continuation of the trends towards energy-dependent intensification. More recently, climate change concerns brought forward both the issue of direct greenhouse gas emissions from agriculture (Garnett 2011; Robertson, Paul, and Harwood 2000) and the use of fossil fuels in the agriculture system (Woods et al. 2010)but also the collectively negative impact of localized climate change on agricultural productivity (Olesen and Bindi 2002; Lal 2004).

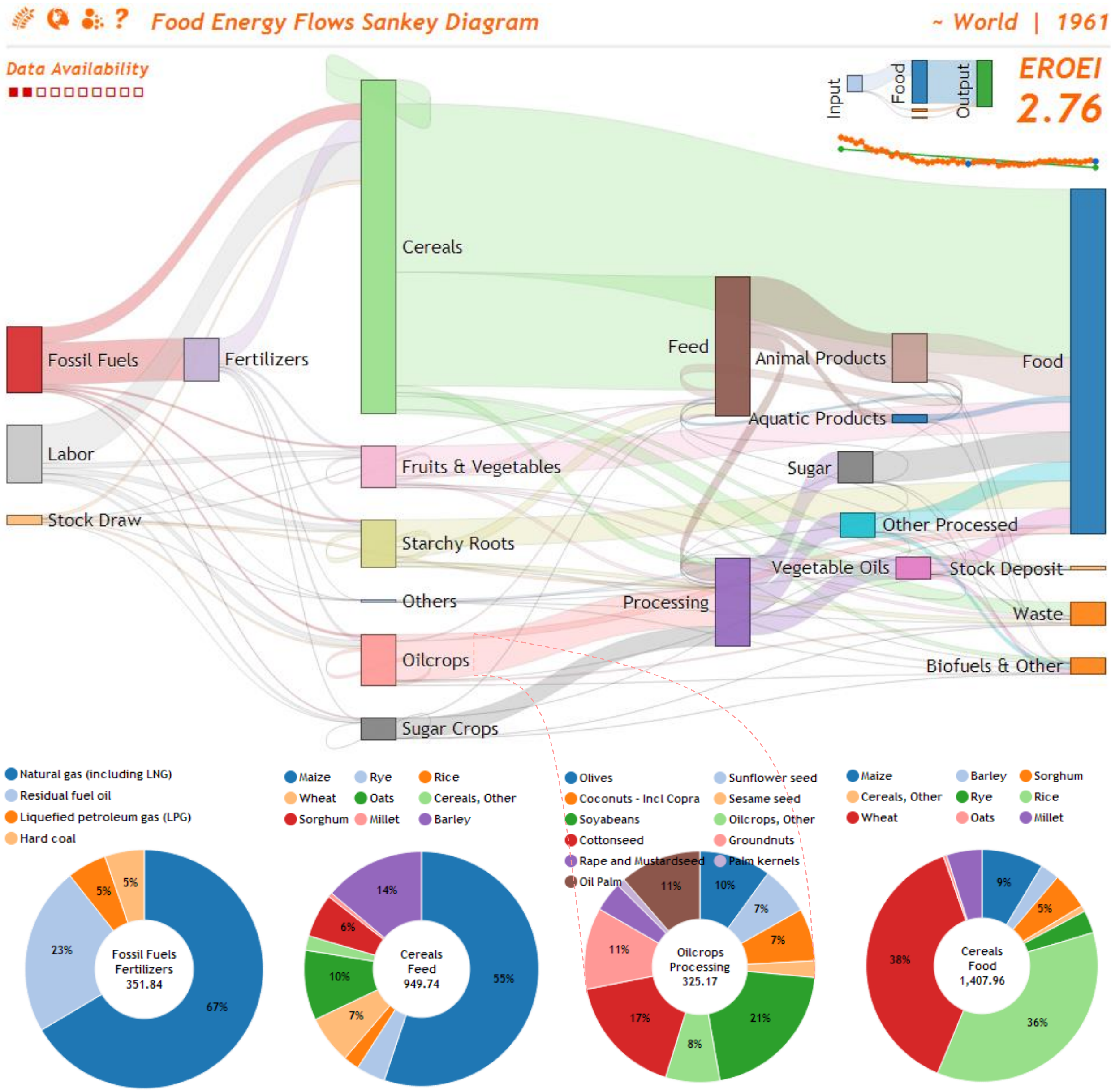
Realizing that with a growing and increasingly affluent population, the energy and food systems will need to converge and be studied in conjunction, the concept of the food-water-energy nexus recognizes this relationship and is gaining traction but so far research focuses on regional/local scales (Bazilian et al. 2011; Markussen and Østergård 2013; Howells and Rogner 2014).

We explore the relationship of the food and energy systems on a global scale especially as it pertains to the forthcoming sustainable energy transition. Using databases by FAO (Food and Agriculture Organization of the United Nations 2014) and World Bank ("World Development Indicators" 2014) we reconstruct a high-resolution energy and material flow map (visualized through Sankey diagrams) of the global agriculture system (agrisystem) on a country level going five decades back. Using Energy Return on Energy Invested (EROEI) as a fundamental metric for assessing the productivity and energy needs of our food system(Dale, Krumdieck, and Bodger 2011; Heffernan 2012; Petherick 2013), we extrapolate current trends to project energy needs of the food systems in the medium-term and what these imply for the use of fossil fuels and the sustainable energy transition to replace them.

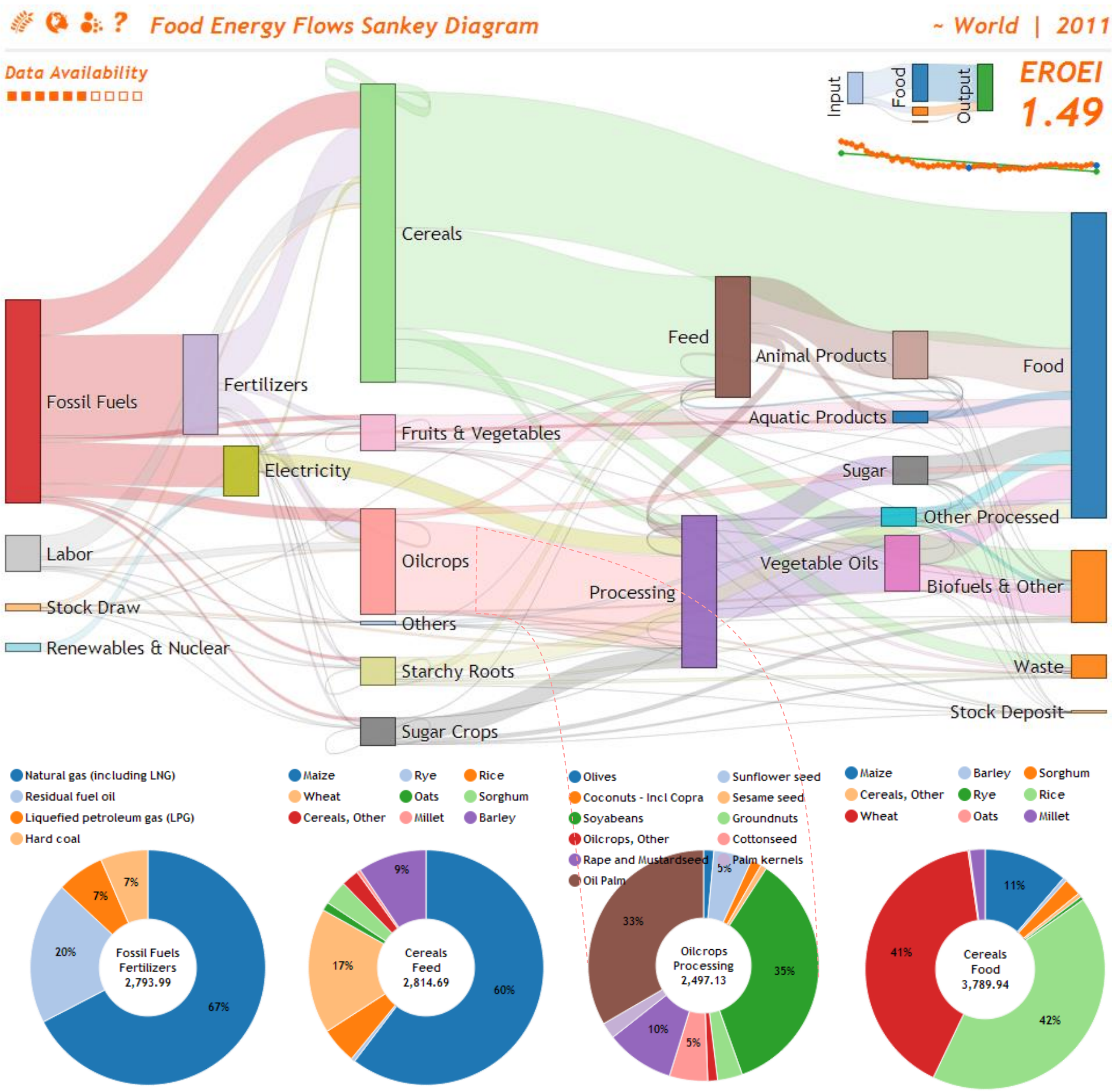
An Energetic view of the Global Agrisystem

The energy flows in TWh of the global agrisystem are shown in Fig. 2 for the years 1961 and 2011 and their derivation is discussed in SM. The flows are shown from left to right split in five stages: primary energy supply (fossil fuels, labor and renewables separated), secondary and embodied energy (in the form of fertilizers and electricity), primary crop categories (cereals, fruits-vegetables-others, oilcrops, starchy roots and sugar crops), intermediate processing (animal (and fish) feed and processed food), and final consumption which aggregates processed (animal products, fish, sugar, vegetable oils) and unprocessed (the primary crops) into total sums for human food, biofuels and industrial feedstock, waste and stock increase. The flows only include the technical energy provided into the system and not the energy captured from natural processes (mainly photosynthetic). We calculate the agrisystem EROEI for every country based on Eq. 1. On a country level the input is augmented by Imports and the output by Exports (not applicable for World aggregate flows).

$$EROEI = \frac{E_{OUT}}{E_{IN}} = \frac{(E_{Food} + E_{Biofuels\&Feedstock} + E_{StockDeposit})}{(E_{Fossil} + E_{RE} + E_{Labor} + E_{StockDraw})} \qquad \text{Eq.1}$$


Food Energy Flows Sankey Diagram
~ World | 1961
Data Availability
EROEI
2.76
Input
Food
Output
Fossil Fuels
Fertilizers
Labor
Stock Draw
Cereals
Fruits & Vegetables
Starchy Roots
Others
Oilcrops
Sugar Crops
Feed
Processing
Animal Products
Aquatic Products
Sugar
Other Processed
Vegetable Oils
Stock Deposit
Food
Waste
Biofuels & Other
Natural gas (including LNG)
Residual fuel oil
Liquefied petroleum gas (LPG)
Hard coal
Fossil Fuels
Fertilizers
351.84
Maize
Rye
Rice
Wheat
Oats
Cereals, Other
Sorghum
Millet
Barley
Cereals
Feed
949.74
Olives
Sunflower seed
Coconuts - Incl Copra
Sesame seed
Soyabeans
Oilcrops, Other
Cottonseed
Groundnuts
Rape and Mustardseed
Palm kernels
Oil Palm
Oilcrops
Processing
325.17
Maize
Barley
Sorghum
Cereals, Other
Rye
Rice
Wheat
Oats
Millet
Cereals
Food
1,407.96

A.



B.

Fig. 2. Global Agrisystem Energy Flows (TWh) in 1961 (A), and 2011 (B) Flows that loop back indicate seeds. Conversions and assumptions are discussed in SM. (Data Sources: Inputs: FAO, WDI (Food and Agriculture Organization of the United Nations 2014; "World Development Indicators" 2014) and own calculations. Outputs: FAO(Food and Agriculture Organization of the United Nations 2014), own calculation). It is important to note that this is not a conventional Sankey diagram, as flow conservation does not hold. Level 3 (Primary Crops) conversions are supraunitary (higher energy output than input, coming mainly from photosynthesis) Level 4 (Animal Feed and Processing) conversions are subunitary (higher input than energy output, coming from the energy required for processing and animal product derivation not already depicted.The piecharts show the breakdown of the 4 largest flows.

Plotting the evolution of the global agrisystem EROEI from 1961 to 2011 along with a shaded band indicating the standard deviation ofnational EROEI values (Fig. 3) we find a consistent trend of the weighted average global EROEI - decreasing fast during the 1960s and 70s, then stabilizing in 1990s and with a tendency for slight increase in 2000s. As expected the EROEI values show a small annual variability caused by the effects of: annual climatic variability (a better year yields a better crop), input variation (e.g. high oil prices reduce the fossil fuel inputs disproportionally reducing the total output), and final product utilization (e.g. a changing ratio of intermediate food products to animal products or biofuels alters system EROEI).

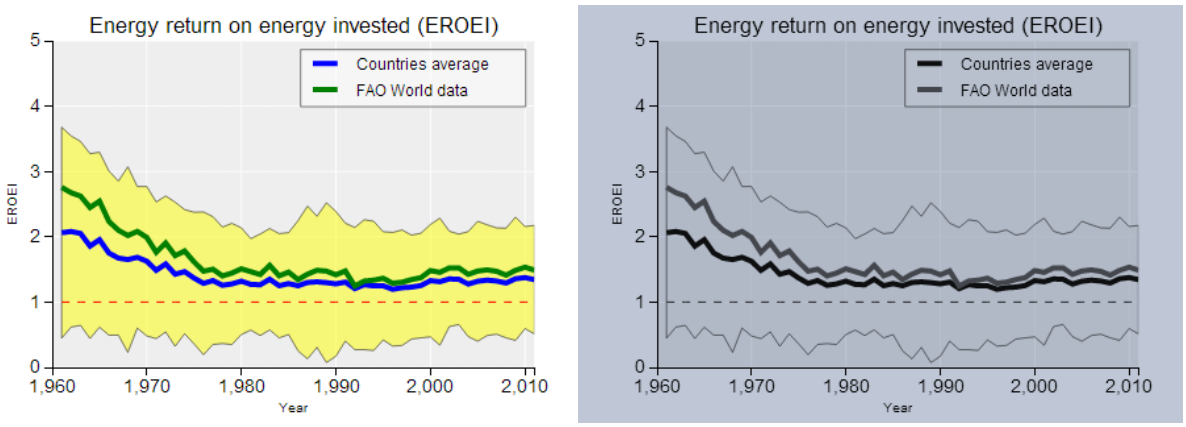
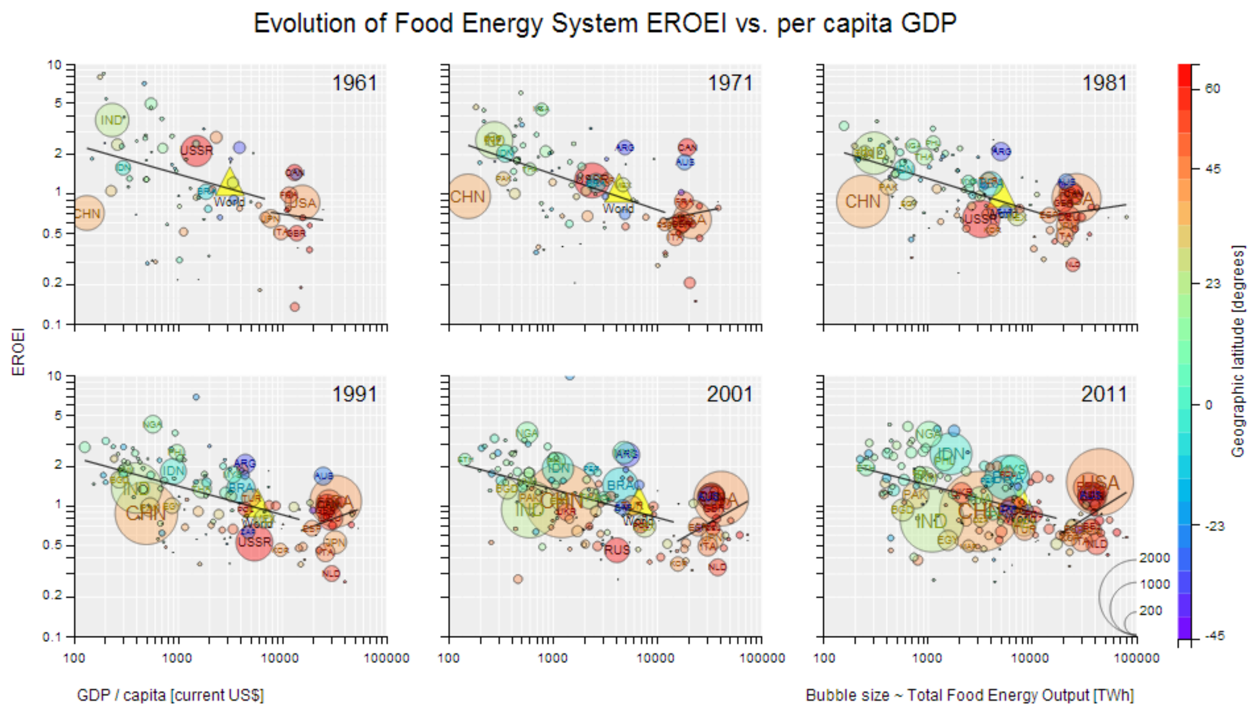
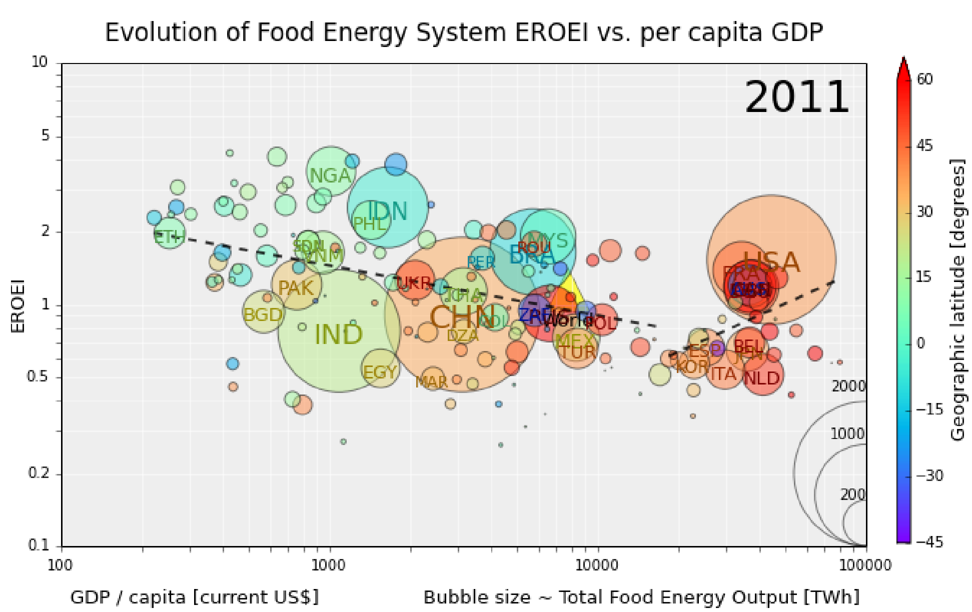


Fig. 3. A: Evolution of Global Agrisystem EROEI and B: Yields/Ha (1961-2011).

A closer observation of the dynamics at hand show that the tradeoff between yields and energy inputs - while yields per hectare have consistently increased, the increase is coming at the cost of greater energy intensity as measured by EROEI – holds across countries. Since the energy-inputs are increasing at a *faster rate* than outputs resulting from yield benefits, this leads to a ne decreasing EROEI. Yields per hectare of mechanized, intensive agrisystems characteristic of developed economies are higher than low-intensity, manual agrisystems (Fig. 4 A and B) characteristics of developing economies but the EROEI of the latter is higher (Fig 4 B & C). Increasing population levels cannot be supported without mechanization and large food-producers undertake this transition (like India, Indonesia, Brazil and Malaysia). At the same time there is a strong correlation between the level of economic development of a country (as measured by GDP/capita) and its agrisystem type, leading to the overall observation that there is an inflexion point of GDP at which EROEI will start to rise again – albeit much slower than the previous drop. This rise comes from the fact that mature agrisystems of developed countries that have been mechanized for decades, start to benefit from the systemic efficiency gains and learning curves, as well as possibly respond to later emissions and efficiency pressures. We observed this inflexion point to be around 15000-20000 $/capita and we will refer to it as the EROEI-GDP inflexion. This phenomenon is illustrated on Fig 5B.



A.



B.

Fig. 4. A: Evolution of EROEI across the past 5 decades vs. GDP/capita (current US$). Bubbles sizes represent the total food energy outputs of countries (TWh), whereas colors represent geographic latitude. There is a qualitative difference of the regression trend for countries past the EOREI-GDP inflexion. Therefore, we present a separate regression line (weighted with total food energy output) for the top 20% of countries, those with the highest GDP/capita. As

expected, the countries with the highest EROEI are equatorial countries with a low GDP/capita and very probably a non-mechanized agriculture. B: The data for 2011 is magnified.

In cross country agrisystem comparisons, the EROEI will depend on the climatic zone of the country but nevertheless, the above trends hold without normalization (Countries even within a certain latitude band exhibit the same trend – equivalent to looking at the trend within points of the same hue on Fig 4.)). It is also important to note that the least fertile latitude bands are those at the Tropics (±23º). Fig 5. illustrates this by plotting irrigation energy intensity against latitude.

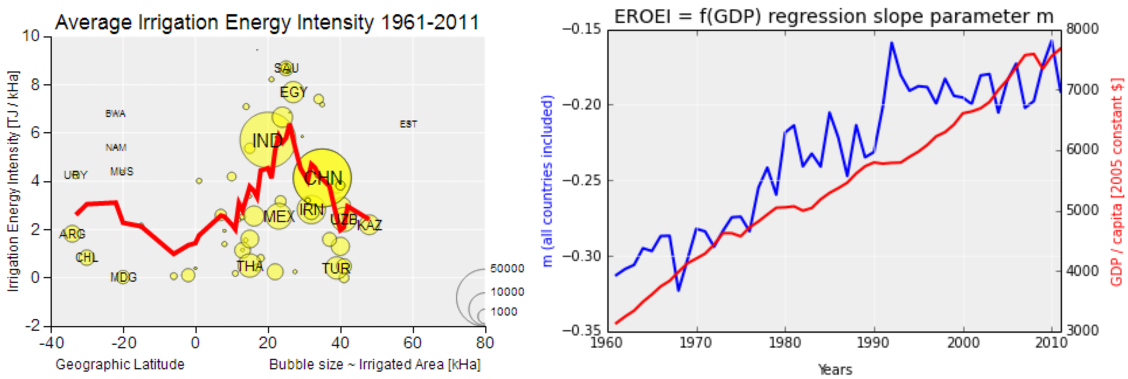


Fig. 5. A: Average Irrigation Energy Intensity (TJ/kHa) for the period 1961-2011 for countries with sizeable irrigation systems installed. The less fertile (reasonably assuming a positive correlation between irrigation and yield) latitude bands of the Tropics emerge. Source ((Food and Agriculture Organization of the United Nations 2014). B: The evolution of the slope parameter *m* of the regressions *EROEI=f(GDP)* (also represented on Fig. 4A) is correlated with GDP/capita, decreasing over the past 50 years, as GDP/capita was increasing. Since the current global average GDP/capita is around 8000 US$, the slope is still negative (regressions are taken over the entire time period 1961-2011 in this case). The EROEI-GDP inflexion is expected to occur when GDP/capita hits 15000-2000 US$, around 2050-2070.

The Sustainable Energy Transition Challenge for the Global Agrisystem

The realizations that (i) EROEI is decreasing with mechanization as yields increase and (ii) fossil fuels consist more than 82.4% of the primary energy input of the global agrisystem are a cause of concern and an action call. Food production should increase from 70 to 100% (Davies et al. 2009) by 2050 to provide for the 9 billion projected population with appropriate nutrition. Maintaining the trend of increasing yields by converting acreage that is currently cultivated with low-intensity agriculture to higher yields through conventional intensification will require significantly more energy input (XXXTWh).

In addition, the adverse impacts of climate change on agriculture (XXX, (Brown & Funk, 2008)) are expected to increase agriculture's energy intensity since crop failures will become more likely, irrigation needs will increase to address droughts, pesticide application will increase to counter the effect of humid streaks, and fertilizers will be needed for cultivating marginal land. This increasing need of energy inputs will occur at a point where the net energy availability of fossil fuels (key inputs in fertilizers and agricultural machinery and transport) are reaching their limits (XXX, (Murray & King, 2012)) – an effect that already reflects on food price volatility especially when correlated to the use of agriculture products for first generation biofuel (XXX).

We project that the technical (i.e. non-labor) energy demand of the global agrisystem to meet UN's medium population projections to the end of the century will increase from XXX to XXX (a XXX%), assuming that (i) the crop ratios determined by nutrition and consumption preferences remain the same (ignoring the trend for higher meat consumption as societies increase their GDP/capita XXX), (ii) the per capita caloric intake is 2500 kcal/day compared to an average of XXX today, (iii) the food-biofuel ratio remains stable (not including third generation biofuels from waste biomass), (iv) the ratio of food waste is halved, and that (v) global agrisystem EROEI decreases further by 10% (a rather conservative estimate that captures the climate effects and intensification requirements).

Following the IPCC recommendations for mitigating the impacts of climate change implies that a significant portion of accessible fossil fuels should be left in place in order to meet a total global carbon dioxide budget of 3010GTonnes CO2, leaving 1200GTonnes to be emitted (XXX). The challenge for the global agrisystem therefore is two-fold as it is called to basically double its energy intake (to provide food for 9 billion people) while moving away from fossil fuels that constitute more than 80% of its energy inputs.

Taking a purely energetic view of society's economic system, our earlier work indicates that the ratio of societally available energy that should be used to invest in renewable energy installation (the renewable energy investment ratio – epsilon) would need to increase at least by an order of magnitude from its current levels within the next twenty years to sustainably meet future energy needs (XXX). If one looks specifically at the agrisystem transition, we find XXX the rate of installation of RE technologies to substitute the current agrisystem energy needs would need to be (XXXGW/year) or it would constitute XXX%.

Like in all systems, the sequence of the transition needs to include demand management – partially substituting meat with the equivalent vegetable nutrition for instance would automatically raise EROEI, resource input efficient utilization – a large percentage of the applied nitrogen fertilizer is actually not used by plants and instead leads to eutrophication (XXX), and of course the substitution of energy sources (electricity input instead of natural gas for fertilizer production). With this in mind, we can run a decarbonization scenario

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Conclusions

The food agriculture system is an unlikely place to support significant additional sources of renewable energy in the form of biomass. It is already currently strained producing food with a deteriorating EROEI as meat consumption and biofuel diversion increase. There are significant opportunities in the form of waste reduction, utilization efficiency, and product yield optimization. Increasing the penetration of potentially energy-systems agriculture systems like permaculture, organic farming, localization and reducing conversion losses in the form of meat consumption will allow the food system to support the needs of the projected growth in human population for the next decades.

This indicates that since the food/agriculture system are likely to be severely affected by climate change (XXX) – science 1973, the energy inputs that will be needed to maintain its productivity would increase.

OTHER NOTES – UNUSED TEXT

XXX an image of the food-energy system and a system boundary drawn should be shown

.Its variance increases exponentially so it is not homoscedastic – as for developed world typical values are 0.8-1.3, second world 1.5-2.5, third world 2.5-5. I think we have to pay attention to the geographic latitude/insolation/soil quality

A portion of the harvested crops is used for direct human consumption, a portion is processed artificially or through animals for indirect consumption, while inedible parts of the plant contain additional energy that could be conceivably utilized. We track the energy balances in these exchanges using the Food and Agriculture Organization (FAO) systematic categorization and data.

This view does not account for land use and erosion but this is not a critical limitation. Land use has been more or less steady. graph? Soil erosion is indirectly addressed by counting the fertilizer application which are supplementing soil nutrients and if accounted for, it would make the numbers look worse (XXX perhaps we can indicate an estimate as an input).

A steady or deteriorating EROEI for agriculture systems is an indicator that if the business-as-usual practices continue, our food/agriculture system would require a substantial ratio of a declining total available energy. Figure 5XXX shows the energy inputs to agriculture in the context of global energy metabolism. Currently, food production utilizes about 4%XXX of the current energy budget. In addition to fossil fuels, it also utilizes a significant percentage of phosphate rock – a non-renewable resource (XXX Kopelaar).

We explore the effects of different human nutritional preferences options on the energy system and yield. The options include maintaining the trend for increasing share of meat products.

The decarbonization rate of agriculture (assuming it is the last user of fossil fuels – as the most critical link).

Figure 5: A Global Energy Consumption by Source and Agriculture. (B) Evolution of Required Yields

If the rate of clean/renewable energy investment does not substantially increase in the near future, it is likely that energy availability will become an issue when it comes to supporting the food system

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