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Energy, nitrogen and farm surplus transitions in agriculture from historical data modeling. France, 1882-2013.

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Abstract

This article addresses agricultural metabolism and transitions for energy, nitrogen, farm production, self-sufficiency and surplus from historical data since the 19th century. It builds on an empirical dataset on agricultural production and production means in France covering 130 consecutive years (1882-2013). Agricultural transitions have increased the net production and surplus of farms by a factor of four and zeroed self-sufficiency. The energy consumption remained quasi-stable since 1882, but the energy and nitrogen structure of agriculture fully changed. With an EROI (energy return to energy invested) of two until 1950, preindustrial agriculture consumed as much energy to function as it provided in exportable surplus to sustain the non-agricultural population. The EROI doubled to four over the last 60 years, driven, on the one hand, by efficiency improvements in traction through the replacement of draft animals by motors, and, on the other hand, by the joint increase in crop yields and efficiency in nitrogen use. Agricultural energy and nitrogen transitions shifted France from a self-sufficiency agri-food-energy regime to a fossil-dependent food export regime. Knowledge of resource conversion mechanisms over the long duration highlights the effects of changing agricultural metabolism on the system's feeding capacity. Farm self-sufficiency is an asset against fossil fuel constraints, price volatility and greenhouse gas emissions, but it equates to lower farm surplus in support of urbanization.

Keywords: Agricultural transitions, energy return on invested energy (EROI), nitrogen use efficiency (NUE), farm self-sufficiency, farm surplus, external energy dependence.

<heading level 1> Introduction

Agriculture is the pillar of urbanization and a key condition for sustaining complex social structures. Yet, material and energy flow analysis in agriculture (agricultural metabolism) is currently given very little attention in industrial ecology studies. The analysis of agricultural metabolism from a historical perspective can provide insights on the complex mechanisms and interactions between resource use and food security. Current concerns about planetary boundaries (Steffen et al., 2015) and dwindling fossil resources can reinvigorate the study of farm system transitions and trajectories as a means of elucidating food sustainability issues. Since 1900, the global population has increased five-fold while areas cultivated for agricultural use have only increased by 67 % (Smil, 2002a), highlighting a major increase in agricultural productivity. This productivity increase is largely due to high inputs of fertilizers, water, pesticides and technological innovation (Vitousek and Howarth, 1991, Postel, 1998, Smil, 1999; Tilman et al., 2002, Mueller et al., 2012) and is characterized by high levels of fossil energy use (Smil, 2002a). High-energy subsidies in vegetal and animal production enhance the energy conversion efficiency of solar radiation into food, but jeopardize food security against fossil fuel depletion or price volatility (UN 2017; OECD, 2017).

Agriculture is not sustainable as long as it relies on fossil-based inputs. However, the replacement of fossil energy by renewables implies that part of the annual resource generation of the planet has to be set aside to meet the system's functional requirements. In other words, the internalization of exogenous resource inputs leads to less surplus generation, which, in the case of agriculture, translates into less food available to society. Surplus generation drives

social structure complexity, large-scale trade and international integration (Boserup, 1981, Grübler, 1998).

A big challenge for agriculture will be to sustain a growing human population within a context of increasing consumption of livestock products (OECD/FAO, 2017) while reducing environmental impacts (Foley et al., 2011) and fossil fuel dependency (FAO, 2011a; UN 2017). In the late 1960s, H.T Odum was the first to highlight the role of fossil-fuels in agri-food system energetics, emphasizing that agriculture is both an energy production and consumption system (Odum, 1967). Transitions in agriculture are complex multidimensional phenomena with economic (Kander and Warde, 2011), sociological (Lobao & Meyern, 2001), technological (Grübler, 1998) and resource use dimensions. Changes in resource inputs modify the internal structure of systems, their functional perimeter and their connections to food processing industries (Kim et al., 2017). Unlike knowledge on transitions at urban (Krausmann, 2013, Kim and Barles, 2012), national (Fouquet, 2010, Krausmann and Haberl, 2002, Haberl et al. 2006, Krausmann et al., 2011) and global scales (O'Connor and Cleveland, 2014; Smil, 2016), very little is known about the energy transitions of agriculture due to the lack of records on agricultural energy consumption.

Energy transitions depend on convertors, resource inputs and consumption patterns which have all changed dramatically with the industrialization of agriculture (Steinfeld et al., 2006; Grübler, 1998). Agricultural industrialization is interlinked with the Haber-Bosch process of ammonia synthesis in industrial nitrogen (N) fertilizer production which underpinned a net doubling in global population (Smil, 2002b; Erisman et al., 2008) as well as the alteration of the global N cycle involving severe effects on ecosystems and human health (Sutton et al., 2011, Bouwman et al., 2011). In addition to enriching the earth with reactive nitrogen (Smil, 2001), industrial N fertilizers are energy-intensive and currently entirely dependent on fossil fuels (Woods et al., 2010).

The concept of energy return on energy invested (EROI) is a relevant indicator for analyzing energy structures in human systems (Pelletier et al., 2011). Inspired by the seminal work of C.S. Hall on the energy yields in fish migration (Hall, 1972), the EROI was later formalized to assess the net energy gains for society for petroleum, gas and electricity generation (Cleveland et al., 1984, Court and Fizaine, 2017). EROI in agriculture indicates the energy ratio between the food or other biomass produce of farms and the energy invested in the system. Most studies focus on specific crops (Bonny, 1992; Okzan et al., 2004; Pracha and Volk, 2011; Murphy et al. 2011a) or livestock systems (Pelletier, 2008; Pimentel, 2004) but only a few assess EROI change in time at regional or national levels (Cleveland, 1995; Hamilton et al., 2013; Markussen and Ostergard, 2013; Galán et al. 2016; Gingrich et al., 2017; Guzmán et al., 2017). Nevertheless, the trade-offs between resource use and EROI in agricultural transitions have received little scrutiny through integrative system approaches fed on continuous data series. This article fills this gap by pursuing a triple objective: (i) integrating energy and nitrogen flow analysis and transitions in agriculture at the national scale; (ii) highlighting the relation between efficiency changes, farm-surplus and self-sufficiency; and (iii) discussing the impact of flow accounting choices on the description of agricultural system trajectories. The article uses France, one of the world's largest agricultural producers, as a reference case. It builds on an outstanding empirical dataset spanning 130 consecutive years (1882-2013) on agricultural production and production means.

<heading level 1> Methods and data

<heading level 2> System boundaries

The study system is agricultural production in France including vegetal and livestock production. The study focuses on the energy and nitrogen flows associated with the

production at the “farm gate” level. The system boundaries embrace all utilized agricultural area in France and include imported feed. Food processing and retailing are excluded. The analysis covers the period from 1882 to 2013 and builds on a continuous and consistent dataset combining data from national statistics (Ministère de l’Agriculture 1898, 1936, 1947 to 1969; INSEE 1961; INSEE 1990; Agreste, 2017) and from the Food and Agricultural Organization (FAO) production and international trade statistical databases (FAOSTAT, 2017).

<heading level 2> Energy metabolism and the EROI of agriculture

The energy metabolism of agriculture is reconstructed by accounting for biomass transformations between, on the one hand, net primary production (NPP) and the exportable biomass surplus of farms and, on the other hand, the energy invested (EI) in support of the production system (fig1). NPP is defined as the total aerial net biomass produced on utilized agricultural area (including all croplands and grasslands), which is the sum of all arable crops production, crop by-products (stalks), and grasses. Crop production is reported in the statistics and excludes on-field crop losses. Crop by-products are estimated from the harvest index (HI) of crops, i.e. the ratio of crop yield to crop’s total aboveground biomass (table S1 in Supporting Information SI). Data on grass production are available in the national statistics for the entire study period. They are estimates based on direct agricultural surveys and model simulations (Agreste, 2001). NPP is converted from mass to gross energy using standard energy values as detailed in SI (table S1).

Extracted NPP (NPP_e) is defined as the sum of all harvested crops, straw and grasses that go into feed and food production and other uses. For grasses, NPP_e includes both harvested and grazed biomass (excluding potential forest grazing). In the period 2001-2010, the ratio of NPP_e to NPP for grasslands is reported equal to 80 % (Agreste, 2013a). This same value is used for the entire study period. For straw, NPP_e varies according to the quantities of straw used as feed. It is reconstructed from data on grain production and on livestock feed formulas for specific dates as detailed in SI (fig S1). The difference between NPP and NPP_e is defined as residual NPP (NPP_r). NPP_r may be landfilled, burnt or recovered as a material, mainly for livestock bedding.

NPP_e becomes net production (NP) which is the sum of the vegetal and livestock output of farms, minus the feed converted into meat, eggs and milk (fig1). The energy return on invested energy (EROI) is then defined as the energy ratio of NP to total EI in the system ($EROI = NP/EI$). NP and EI are defined in the following subsections.

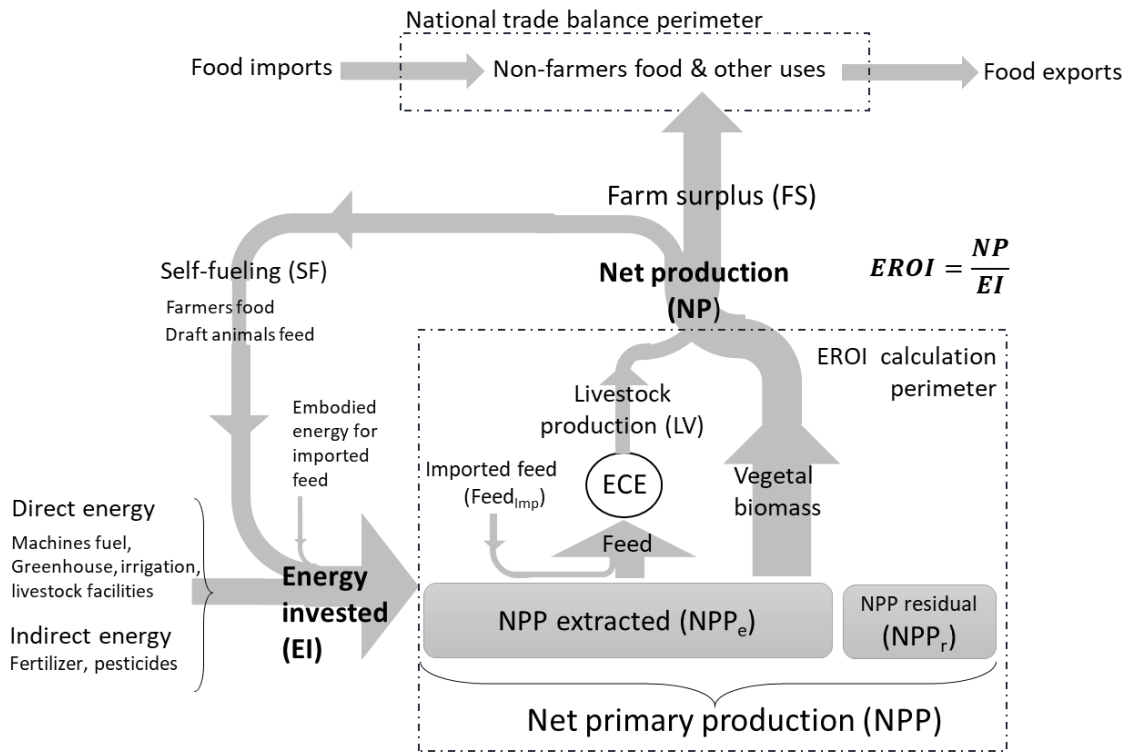


Figure 1 Energy flows in agricultural systems and energy return on energy invested EROI calculation perimeter. ECE is energy conversion efficiency from feed to livestock production. The magnitude of flows is substantially different before and after agricultural industrialization.

<heading level 3> Net production of farms

Net production (NP) is calculated as the sum of domestic NPP_e , plus the livestock production (LV) minus the livestock feed modeled from livestock energy conversion efficiency (ECE) in historical perspective (Harchaoui and Chatzimpiros, 2017), plus the imported feed ($Feed_{imp}$) (FAOSTAT, 2017) (equation 1). Imported feed needs to be added to domestic NPP_e to equilibrate the energy balance of the livestock sector. LV accounts for carcass, milk and eggs (excluding animal fats and offals) based on total production data (including meat and milk from draft animals) harmonized over the study period following the FAO definition of indigenous production (defined as indigenous animals slaughtered plus the exported live animals of indigenous origin, FAO, 2011b). The ECE calculation proposed by Harchaoui and Chatzimpiros (2017) is here extended to the 19th century and considers cereals straw as an additional feed material (fig S1 in SI). NP is divided into the energy reinvested in the system, (self-fueling) and the exportable biomass to non-agricultural population (farm surplus).

$$NP = NPP_e + LV \times \left(1 - \frac{1}{ECE}\right) + Feed_{imp} \quad (1)$$

<heading level 3> Energy invested

The energy invested (EI) in the production system is the sum of the energy inputs from internal and external sources (fig 1). Energy from internal sources is a key factor in preindustrial systems. In this article, the EI from internal sources (i.e. energy produced and consumed by the system) is defined as self-fueling (SF). Energy self-sufficiency is calculated as the ratio of SF to total EI.

Self-fueling

SF has been given little attention in the scientific literature so far. It has been typically treated as an internal flow (a quantity of energy that is simply ignored as input and output) (Steinhart and Steinhart, 1974; Stanhill, 1984) rather than as a through flow (i.e. an output flow reinvested as an input in the system) (Cleveland, 1998). An intermediate approach would account for human labor as a through flow and for draft animal power as an internal flow (Guzmán, et al, 2017). Whereas energy balance is respected in all approaches, the internal flow approach loses sight of the actual energy invested in the system. To allow for a consistent accounting and trade-offs between SF and external inputs during agricultural industrialization, we argue that SF has to be addressed as a through flow. In this article, SF is reconstructed in terms of primary energy as the sum of food for human labor and feed for draft animals. For draft animals, SF is calculated from standard values of energy requirements during work and rest (Smil, 2008) and data on draft animal numbers (fig S2 in SI). SF for farmers is calculated from data on active agricultural population multiplied by the annual food intake per farmer (Toutain, 1971; FAOSTAT, 2017). Calculation details are given in SI.

External inputs

EI from external sources includes direct and indirect inputs as summarized in figure 1. Direct inputs are calculated for traction machines (tractors and combine harvester-threshers), irrigation, greenhouses and livestock facilities (heating, lighting and ventilation). Indirect inputs correspond to the energy embodied in imported resources and are calculated for industrial fertilizers (N, P, K), pesticides and imported feed. Imported feed is assigned an embodied energy content corresponding to synthetic N fertilizers and on-field traction (see SI). Energy relating to the construction and maintenance of agricultural machinery and farm buildings, as well as resource transportation to the farms, is not included.

Energy inputs for traction machines—tractors and combine harvester-threshers—is denoted as machines fuel (MF) and calculated with equation (2).

$$MF = (F \times P_{nom} \times LF \times WT) / CE \quad (2)$$

where F, the machines fleet; P_{nom} , the nominal power; LF, a load factor denoting the fraction of nominal power actually in use; WT, the working time per year and machine and CE the conversion efficiency of fuel to mechanical energy. Detailed data are provided in SI.

Energy inputs for irrigation, greenhouses and livestock facilities are respectively reconstructed as a function of the areas equipped with irrigation systems, the heated areas of greenhouses and the annual volume of livestock production considering energy intensity factors from national statistics as described in SI.

Indirect energy inputs are reconstructed from annual data on the use of fertilizers (N, P, K), pesticides and imported feed, and considering standard embodied energy values for each category derived from literature (Pimentel, 1980; Piringer and Steinberg, 2006; Pimentel and Pimentel, 2008, see SI).

<heading level 3> Farm surplus

Farm surplus is defined as the difference between the NP of farms and SF. Seed is not subtracted from NP because of unavailable data on seed sowing quantities over the study period. The farm surplus measures the biomass export capacity of agriculture in support of non-agricultural population. At the country level, if the farm surplus exceeds domestic demand, the country is a net exporter of agricultural biomass; otherwise it is a net importer (fig1).

<heading level 2> Nitrogen metabolism and nitrogen use efficiency

The calculation framework of the N metabolism of agriculture is described in figure 2. The N use efficiency (NUE) is the ratio of N output in net production (N_{NP}) to total N inputs (N_{tot}) ($NUE = N_{NP}/N_{tot}$). N_{NP} is calculated using the N contents of table S1 (SI) as the sum of N in NPP_e (N_{NPP_e}), plus N in animal production (N_{LV}) minus N in feed derived from livestock N conversion efficiency (NCE) modeling (Harchaoui and Chatzimpiros, 2017) (equation 3). N_{tot} is the sum of biological N fixation (BNF), mineral N fertilizers (N_{ind}), N in imported feed ($N_{Feed_{imp}}$) and atmospheric N deposition (N_{atm}). Note that manure N is not an N input but an internal transformation N flow. N self-sufficiency is calculated as the ratio of local N (the sum of BNF and N_{atm}) to total N inputs.

$$N_{NP} = N_{NPP_e} + N_{LV} \times \left(1 - \frac{1}{NCE}\right) + N_{Feed_{imp}} \quad (3)$$

The BNF rate (BNF_r in kg N/ha) in leguminous meadows and grasslands is subject to change with agricultural practices. There are no available data on BNF. BNF is estimated as a function of agricultural yields for each fixing grass type from equation (4). BNF rates are then integrated on total fixing area.

$$BNF_{r_i} = Y_i / NHI_i \times N_i \quad (4)$$

where Y_i is the harvested yield (kg/ha), N_i the N content of each vegetal material and NHI_i the N harvest index taken at 60 % for leguminous meadows (Anglade et al., 2015) and at 80 % for grasslands. N in imported feed is calculated from international trade data (FAOSTAT, 2017). Atmospheric N deposition is estimated for a uniform deposition rate of 5 kg N/yr/ha of agricultural area. The NUE calculation assumes no change in the soil N reserves.

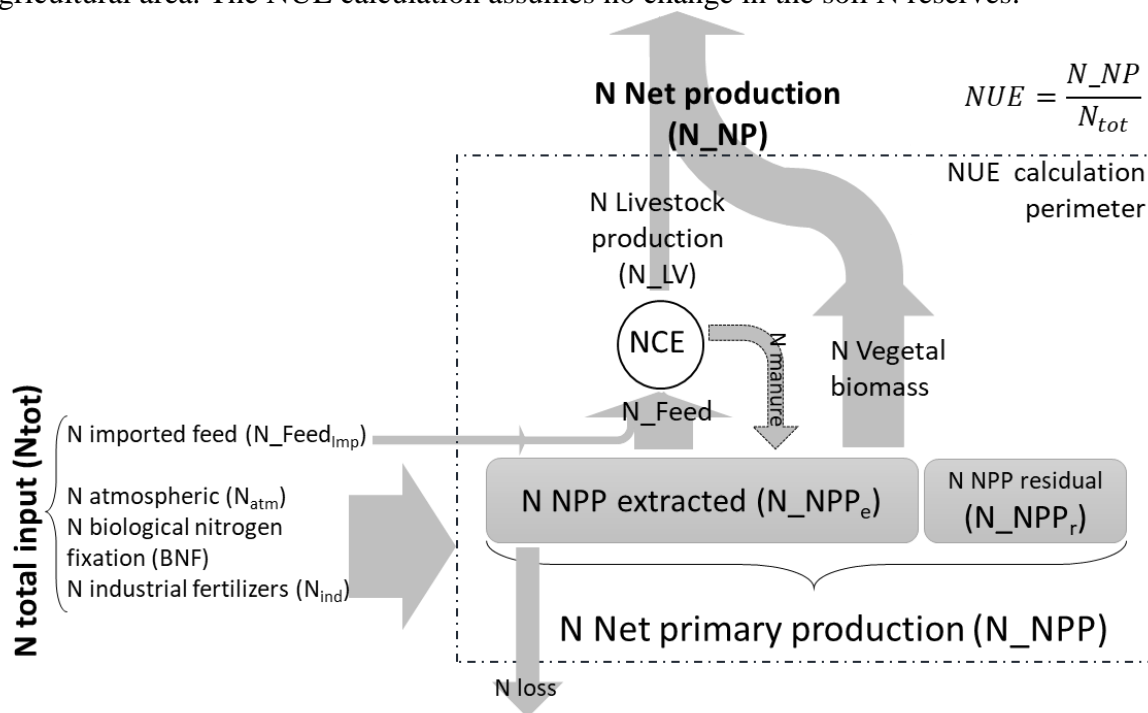


Figure 2 N flows in agricultural systems and N use efficiency (NUE) calculation perimeter. NCE is the nitrogen conversion efficiency of feed to food in livestock production.

<heading level 1> Results and discussion

<heading level 2> Farm production

Figure 3 presents total NPP over time. NPP fluctuated around 1500 PJ from 1880 to 1950 and almost tripled between 1950 and today. The domestic extracted NPP (NPP_e) doubled from about 1300 PJ to 2700 PJ and the share of cereals grain increased from 23 to 43 %. The production of cereals was propelled by high yield increases (fig 4b) and from HI improvements - meaning more grain in total phytomass. The dashed area in figure 1 distinguishes the amount of residual NPP (NPP_r) which consists of unused crop by-products and non-grazed grasses. The volume and share of NPP_r increased along with agricultural yields and along with the reduction of straw in animal rations. Today, only about 35% of total straw production is harvested and only about 2 % is fed to livestock, against a 90 % use as feed until the mid-20th century.

Besides a reduction in the agricultural area, the net production of agriculture increased three-fold over the study period (fig 5a) driven by increases in the agricultural yields and in the conversion efficiency of vegetal to animal energy (ECE) and proteins (NCE) (fig 4a). However, the growth pace of production is decelerating which is in line with observations in a set of other European countries (Gingrich et al, 2015). On the one hand, the deceleration is due to the increase of livestock production which implies higher dissipation of vegetal biomass. Dietary transitions towards higher shares of livestock products tend to reduce net production. In France, the share of animal products in net production doubled from 16 to 34 % over the studied period. On the other hand, net production seems to be reaching a plateau due to crop yields saturation (fig 4b). The general trend of the productivity increase over the study period is punctuated by heavy drops at specific years due to droughts (1893, 1976, 2013) and flooding events (2016). In 2016, cereals production went 20 % down reaching the level of the 1980s.

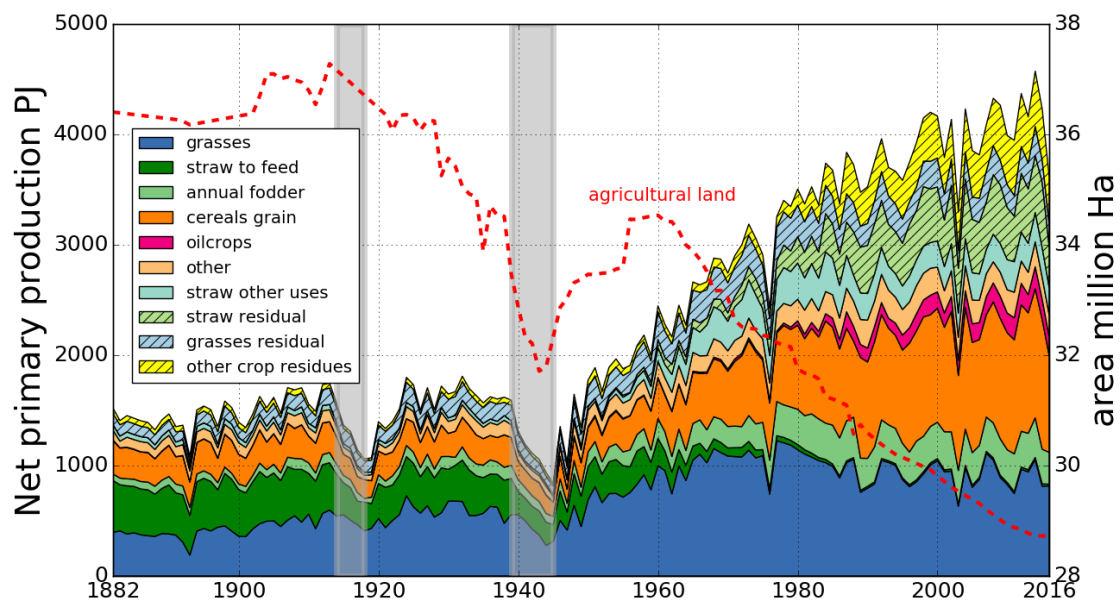


Figure 3 Net primary production (NPP) in PJ. The non-dashed areas add-up to NPP extracted (NPP_e) for food, feed and other uses. The dashed areas are residual NPP. The dotted line is total agricultural area over time in Mha.

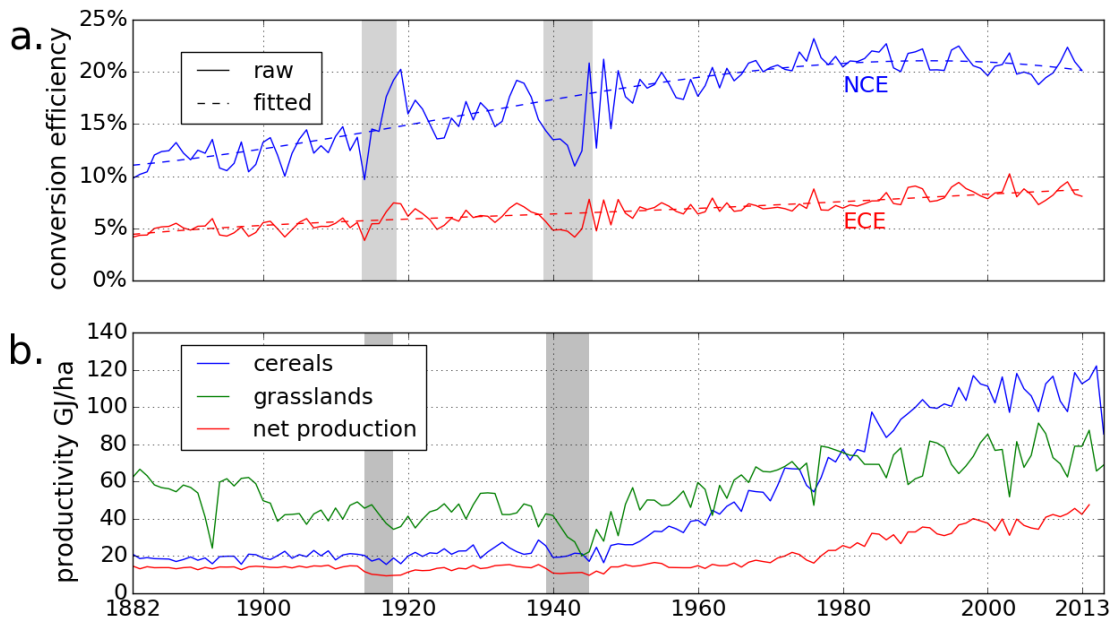


Figure 4 (a) Aggregate livestock energy conversion efficiency (ECE) and nitrogen conversion efficiency (NCE) (b) Agricultural productivities for cereals, grasslands and net production in GJ/ha.

<heading level 2> Agricultural energy transition and EROI

The agricultural energy transition unfolded over three decades. Agricultural machines appeared in the late 1920s and, by 1960, the share of fossil fuels in the agricultural energy mix had grown to exceed 50 % (fig 5a). The number of tractors increased from 27,000 in 1929 to more than 1 million today, with a peak of 1.5 million in 1983. The share of farms owning at least one tractor increased from 16 % in 1955 to 80 % in 1983 (Ministère de l’Agriculture, 1985). Today, there are more tractors than active farmers in France. Increases in machine fleet sizes corresponded with increases in machine horsepower. The nominal power of tractors scored a four-fold increase since 1948, and that of combine harvester-threshers, a five-fold increase, with a doubling over the last 15 years.

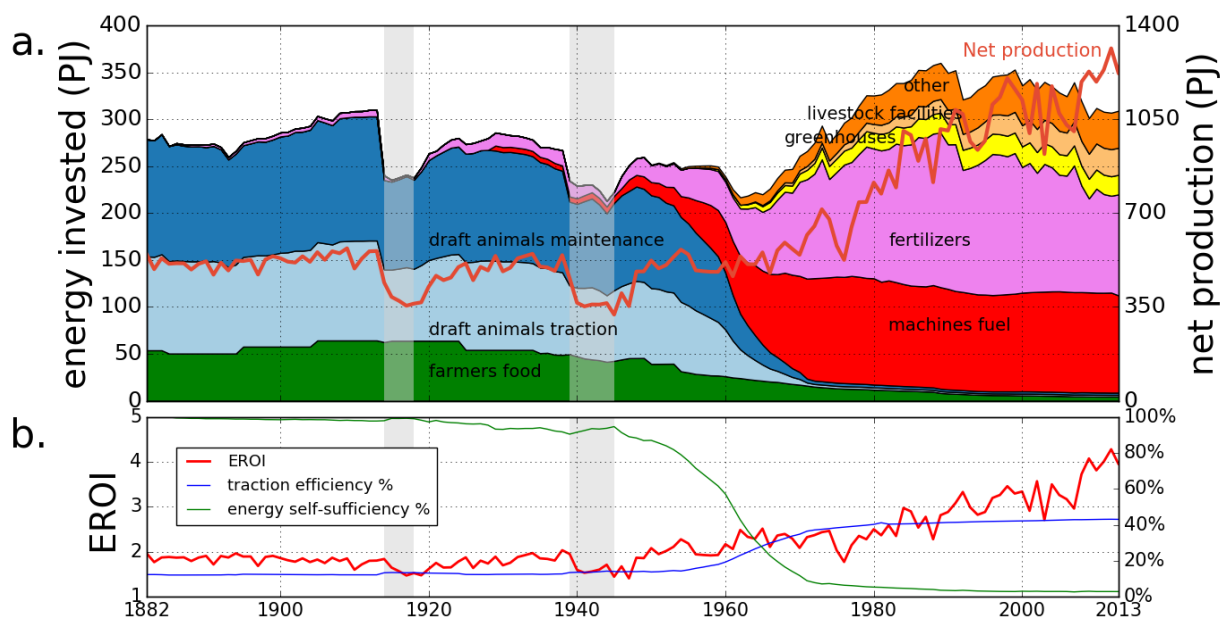


Figure 5 (a) Energy invested per source (PJ) and net production (PJ). Self-fueling is the sum of farmers' food and of draft animal feed for traction and maintenance. Other include energy for irrigation and embodied energy in pesticides and imported feed (b) Energy return on energy invested (EROI), traction efficiency (%), energy self-sufficiency (%)

Energy invested increased by only 15 % between 1882 and 2013 – with a peak by the early 1990s – but the sources of energy changed dramatically (fig 5a). Domestically grown feed and food supplied virtually all energy invested until the end of World War II, against an energy mix composed today of 80 % fossil fuels, 15 % non-renewable electricity and 5 % domestic biomass. The transition involved the quasi-total loss of the system's energy self-sufficiency (fig 5b). The EROI of agriculture displays two distinct phases, reflecting the full transformation of the system's energy structure (fig 5b). With an EROI of two until 1950, preindustrial agriculture consumed as much energy to function as it provided in surplus to sustain the non-agricultural population. The EROI has progressively doubled to four over the last 60 years, driven by energy efficiency growth per unit of net production. For traction, higher efficiency is achieved through the replacement of draft animals by motors, which are more efficient than muscles during work, and which are switched-off when not in use. Indirect energy inputs started by 1945, with the dependence of farms on industrial fertilizers, pesticides and imported feed. Today, the indirect energy consumption of agriculture is as high as the direct consumption. Each represents about 2.6 % of the French national energy consumption. However, in official energy accountings, the indirect energy consumption is conventionally assigned to the industrial sector (Arizpe et al., 2011). In sum, agriculture represents a small share of total fossil fuels use, but the overwhelming share of fossil fuels in the agricultural energy mix puts food security at risk.

It is noteworthy that the EROI of agriculture increased over time, in contrast to the decreased EROI of fossil fuels (Guilford et al., 2011; Court and Fizaine, 2017). This difference reflects the fact that fossil fuel reserves are exploited in an order of decreasing resource quality, meaning that the untapped fossil stocks are expected to supply less energy per unit of energy invested than the past reserves. In contrast, solar radiation is invariable in quality and is captured and transformed more or less efficiently depending on the production means used.

As highlighted by Murphy et al (2011b), EROI analysis is sensitive to system boundaries. For agri-food systems, the broader the system perimeter, the lower the EROI as the energy invested adds up along food processing stages for a given food output (Pelletier, 2008). For instance, in 2011, the food processing industry in France consumed 214 PJ (Agreste, 2013b), which would bring the modeled EROI down to 2.4. In addition, the embodied energy in agricultural machinery can be estimated at 80 PJ by assuming specific weight of 64 kg/kW, energy intensity of 140 GJ/ton and 10 years lifespan of machines (Aguilera et al., 2015), which would bring the EROI further down to 2.1. If energy invested in food retailing, storage and cooking is also considered, total food EROI could fall below 1. Nonetheless, unlike for oil or biofuel projects where an EROI below 1 is nonsense and may justify the abandonment of production (Pimentel and Patzek, 2005), food must keep being supplied whatever energy it takes.

<heading level 2> EROI comparisons with literature

Comparisons of EROI are difficult among studies due to major methodological discrepancies concerning the choice of system boundaries and the ways for which energy flows are accounted within the system. Likely, the greatest discrepancy in relation to system boundaries lies on the way imported feed is accounted for. Previous studies have accounted for imported feed as an input similar to oil and electricity by adding its caloric energy content to the EROI denominator (Galán et al., 2016; Guzmán et al., 2017; Gingrich et al., 2017). In this article, imported feed is accounted for in the EROI denominator in terms of embodied energy. We argue that the EROI denominator should not aggregate the energy invested as power to the system with the feed converted into food. Otherwise, the calculation would be inconsistent because EROI and ECE would depend on whether the livestock is fed on domestically grown or imported feed. ECE and EROI are two clearly distinct indicators, measuring energy efficiency at two different system levels.

Discrepancy in the accounting of energy flows depends on (1) whether self-fueling is treated as an internal flow (i.e. an amount of energy canceled out between inputs and outputs) or as a through flow (i.e. an energy output explicitly reinvested as an input in the system) and (2) whether draft power and human labor are accounted for as primary energy or final power. These choices are critical and may lead to contradictory findings, especially for transition periods where the rate of energy self-sufficiency changes. Previous studies have calculated declining EROI during agricultural industrialization by considering self-fueling from draft animals as an internal flow (Stanhill, 1984 based on Deleage et al. 1979; Allaire and Daviron, 2017 based on Bayliss-Smith, 1982). The industrialization process has primarily occurred from 1945 to 1975 in western countries and is characterized by the shift from internal to external energy sources. We argue that the internal flow approach is inappropriate for transition periods because it simply measures agricultural productivity per unit of human labor and external inputs. Accordingly, the EROI of preindustrial systems is overestimated and any transition to fossil fuels automatically translates into increased energy inputs. This is misleading with regards to total system energy efficiency. In particular, for French agriculture, Stanhill (1984) based on Deleage et al. (1979) reports a 70% decrease in the ratio of energy output to input between 1945 and 1975 in contrast to a 40% increase if self-fueling is considered (fig 6).

With regards to choosing between primary energy or final power as an accounting method for labor inputs, we argue that primary energy is what counts from a resource perspective. In the case of draft animals, final power is only about 10 % of the primary energy mobilized for work, meaning that the final power approach underestimates the energy cost of preindustrial systems by an order of magnitude. Note that for human labor, there is an ethical dilemma

regarding the consideration of farmers' fair share of food intake as energy input in the EROI calculation (Fluck, 1992; Ibarolla-Rivas et al., 2016). In this article, farmers' labor is accounted for as the primary energy content of the food intake not because farmers are only considered as manpower, but because they are irreducible parts of the production system.

The discrepancies described above make EROI comparisons among countries delicate. However, factors such as bioclimatic conditions, production specialization and efficiency in the use of fertilizers greatly affect the EROI and may partially explain differences among studies. For instance, for a given country, a decreasing share of livestock production in favor of high yielding crops grown under favorable agro-climatic conditions and careful nutrient management practices tends to improve EROI. These conditions have developed progressively in French agriculture and may explain differences with the declining EROI reported for Austria (Krausmann et al., 2003), Spain (Guzmán et al. 2017) and Turkey (Okzan et al. 2004). In terms of agricultural specialization, between 1961 and 2013, Austria displays a quasi-stable ratio of meat to cereals production compared to a reduction by half for France (FAOSTAT, 2017). By comparison to Spain and Turkey, agricultural yields in France are at least two times higher and are sustained by regular rainfalls and low irrigation (Daccache et al, 2014). In Spain, the energy for irrigation accounts for as much as 40 % of total direct energy invested (Guzmán et al., 2017) compared to just 5% in France. The EROI increase in France matches the one calculated for the United States between 1970 and 1990 (Hamilton et al., 2013), a period in which both countries display similar increases in cereals yields. A major additional driver of EROI trends is NUE. Today NUE is significantly higher in France than in Spain and Turkey (Lassaletta et al., 2014). Higher NUE translates into lower embodied energy losses per unit of production. Last, EROI may also increase with the average size of farms, which in France is about 2.5 times bigger than in Austria and Spain (Eurostat, 2017). Bigger farms may facilitate economies of scale in relation to the use of agricultural equipment and associated fuel consumption.

<heading level 2> N transition and NUE

The N transition started shortly after the invention of the Haber-Bosch process of ammonia synthesis in 1913 (Smil, 2011), but unfolded much more slowly than the energy transition, as it took half a century before industrial N fertilizers exceeded BNF inputs to agriculture in the mid-60s (fig 6a). N self-sufficiency dropped from 93 % in 1892 to 19 % today (fig 6b). NUE displays a complex trend involving two opposed phases.

First, a century-wide period from the late 19th to 1970s is characterized by a long and sharp drop of NUE from 90 to 25 %, half of the decrease occurring between 1950 and 1970. The decline correlates to the increase in net N production in a context of unprecedented abundance of industrial fertilizers and loose environmental policies stimulating high land productivity (CGP, 1946). The N transition today appears as an open-field experiment for agriculture which enabled economies of scale and the decoupling of vegetal and animal farming (Cowling and Galloway, 2002). In full contradiction with traditional agriculture, decoupled crop and livestock systems hamper the recovery of manure N into further crop biomass and increase N losses (Chatzimpiros and Barles, 2013). N recovery from manure to cropland was the cornerstone of productivity maintenance in preindustrial systems and the key factor of the high NUE during the first half of the 20th century. Notwithstanding, NUE above 100 %, as in 1893, possibly indicates N mining from agricultural soils due to unusually low productivity in BNF crops and normal yields in cereal crops.

The second period runs from the late 1970s to the present, and is characterized by a doubling of the NUE to 50 %, alongside a tripling of the major crops' yields. Often, the increase in crop

yields through increasing fertilization involves diminishing returns in terms of NUE (Tilman et al., 2002), as observed during the first period. Here, the concomitant growth of productivity and NUE suggests a “golden age” for land intensification thanks to improved farmer practices guided by effective nutrient management directives (EU Nitrates Directives, 1991). Today, France counts 50 % more net N production with 20 % less N inputs than in the 1980s (fig 6a). There is little room for further improvements of NUE at the crop level - which is 70 % in wheat production for yields of 7 t/ha (Lassaletta et al., 2014). Instead, a better spatial integration between crop and livestock systems is likely to improve manure N recovery and total NUE. In addition, because industrial N fertilizers are energy intensive, any NUE improvement translate into energy savings and therefore improves EROI. Contrary to the multiplicity of EROI calculation approaches, the NUE calculation framework is less debated in the scientific literature, but long term approaches are rare and focus on crop systems (Lassaletta et al., 2014, Yuan and Peng, 2017) rather than country-level NUE.

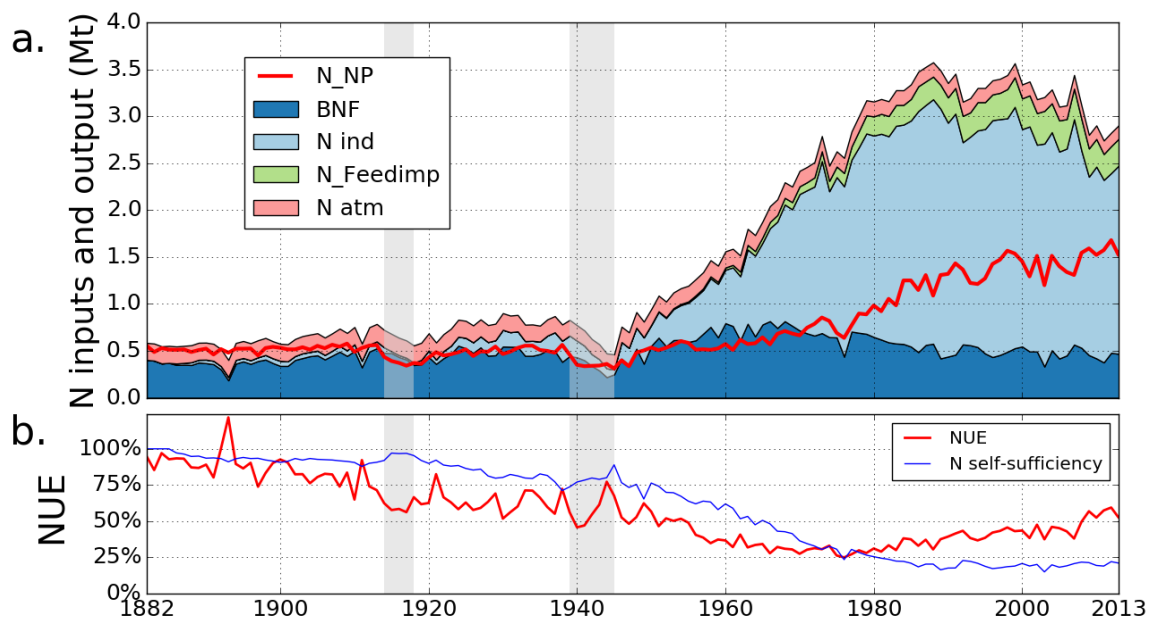


Figure 6 (a) Total N inputs (Mt) as the sum of biological nitrogen fixation (BNF), industrial N fertilizers (N_{ind}), N in imported feed ($N_{Feed,imp}$) and atmospheric N deposition (N_{atm}) versus N output in net production (N_{NP}) (Mt) (b) Nitrogen use efficiency (NUE) and N self-sufficiency (%) over time.

<heading level 2> Farm surplus, land sparing and food regime change

The energy and N transitions diverted France from a self-sufficiency, agri-food-energy regime to a fossil-dependent, food-export regime (fig 7). At the top of fig7, the energy equivalent of imported feed and food in France is reconstructed from FAOSTAT data to denote the amount of biomass that would not be available as farm surplus in the absence of imports.

The agri-food-energy regime shift concerns both agricultural self-sufficiency and food self-sufficiency at the country-level. Until 1950, France formed a food unity with domestic demand equaling farm surplus; today, domestic demand absorbs nearly all livestock production, but only a fourth of the vegetal farm surplus (fig 7). For agriculture, the disruption of self-sufficiency during the transition translated into additional farm surplus. By replacing farmers and draft animals, fossil-fueled machines reduced self-fueling faster than fleet growth

due to higher energy efficiency of machines compared to muscles. For instance, from 1955 to 1975, the number of draft horses decreased ten-fold from 3 to 0.1 million (see SI), allowing the conversion of 3 Mha previously cultivated with oats for feed to additional food production. Oats accounted for as much as 45 % of total cereal land in France in 1929 compared to 5 % in 1983. Likewise, areas cultivated with alfalfa, clover and sainfoin, the primary BNF crops in temperate climates, grew from about 2.5 Mha in 1882 to more than 3.2 Mha in the mid-60s (10 % of the agricultural area). Today, these crops constitute just 0.2 Mha. Synthetic N fertilizers currently supply 2 Mt N, which is equivalent to 8 million “ghost” hectares of BNF crops (fixing 250 Kg N/ha), or 30 % of total agricultural area in France. In sum, the outsourcing to industry of the energy and N requirements of agriculture allowed the reallocation of at least 320 PJ of net production to farm surplus (fig 7).

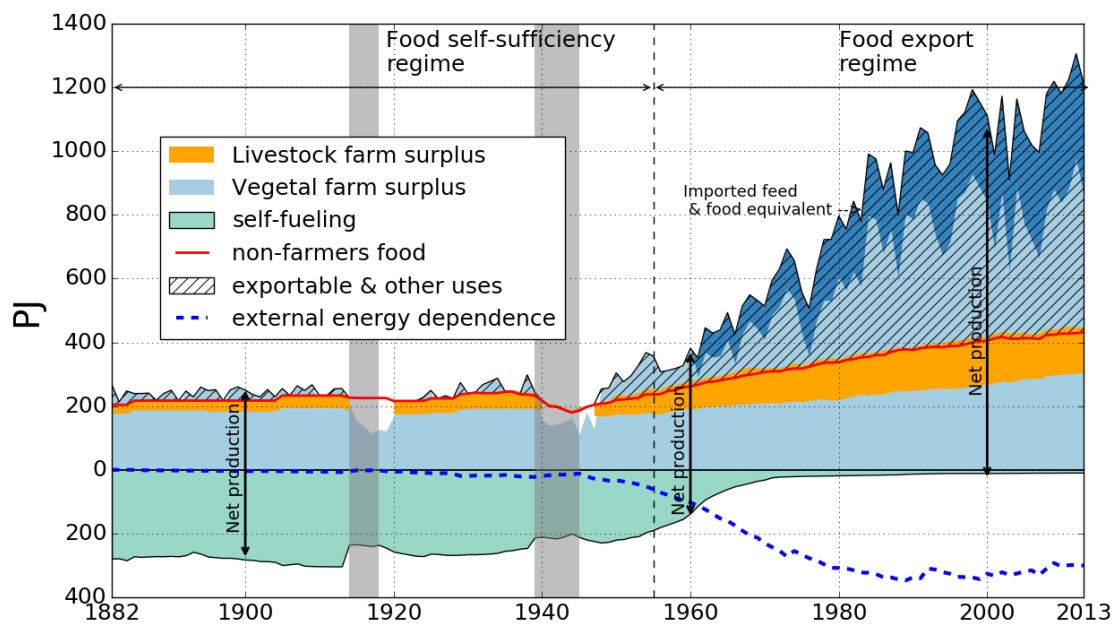


Figure 7 Net production over time as the sum of self-fueling and farm surplus. Farm surplus is compared to domestic food demand (red line) keeping track of the energy dependency on external sources (dotted line). Livestock production (orange area) is split into domestic consumption (below the red line) and international exports (above the red line). The food regime change indicates the double shift from an agri-food-energy self-sufficient regime to a large-scale food export regime dependent on external energy sources. All energy is expressed in PJ.

<heading level 2> Uncertainty

Uncertainty in this analysis is managed through the systematic validation of the modeling results with available data. On the one hand, the simulated consumption of machine fuel matches well with all of the published survey data on the fuel consumption of farms, available at specific dates from 1938 to 2011 (fig S6 in SI). According to date-specific national surveys, machine fuel accounts for more than 60 % of total direct energy inputs to agriculture (Ministère de l’Agriculture, 1979; Agreste, 2014). Accordingly, the uncertainty regarding direct energy is most probably low. On the other hand, the embodied energy in N, P, K fertilizers accounts for the largest share of indirect energy inputs and is calculated considering average values in current fertilizer industries (Piring and Steinberg, 2006). As a result, the indirect energy inputs are possibly slightly underestimated before 1980, given the decrease by

around 40% in the energy intensity of fertilizer production over the 20th century (Smil 2001; Aguilera et al, 2015). Accordingly, the EROI of agriculture is likely to have increased at a slower pace than calculated before 1980 and at a faster pace afterwards. Today, uncertainty in the EROI is estimated at about 20 % depending on whether minimum or maximum values instead of average values are used for the embodied energy of fertilizers (see SI). The calculation of farm surplus presented in figure 7 matches well with FAOSTAT data on product utilization (fig S7 in SI). For the preindustrial period, uncertainty is more difficult to assess due to unavailability of validation data. Our main assumptions are the share of grasses and straw used as feed among total grass and straw production. These assumptions may impact the ECE and, thereby, net production and farm surplus. However, the assumptions used are in agreement with previous studies (Toutain, 1961) and the trajectory calculated for ECE is consistent with values in literature (Smil, 2000). Lastly, the assessment of uncertainty regarding potential soil N reserves change over time is not feasible in this study, but its impact on total system N budget and NUE is expected to be small by comparison to the magnitude of the annual N flows.

<heading level 1> **Significance and conclusions**

Throughout the study period, agriculture drifted away from a self-sufficiency regime built on renewable resources to a fossil-fueled land intensification regime (Krausmann, 2004; Gingrich et al., 2017). The interplay between self-sufficiency and farm surplus is ineluctable and highlights the effect of agricultural metabolism on the system's feeding capacity. The generation of farm surplus is a key socio-metabolic variable and involves deep socioeconomic transformations (Krausmann et al., 2008). The greater the farm surplus, the bigger the human population that can be sustained in cities, and the bigger the capacity of a country to integrate agri-food globalization networks. In France, the agricultural population (farmers plus families) dropped from 48 % in 1880 to only 3 % - or 3,5 million - in 1999 (Agreste, 2009) while net exports increased 20-fold, from 4.2 % of net production in 1961 to 31 % in 2014. The changing share between farmers and non-farmers population illustrates the structural transformations of society in function of the energy regime of agriculture. The reliance on external high-energy subsidies highlights to what extent agriculture forms today an intricate system with industry and how much it deviates from a renewable resource system.

The present analysis goes far beyond numerical results for France by providing a general framework for assessing agricultural metabolism and associated resource conversion mechanisms and efficiencies in support of complex social structures. Agricultural production efficiency increased both due to the energy efficiency gains in combustion engines, which are common to any sector (i.e. transport, chemical industry), and to improvements specific to agriculture. These latter primarily include the selection of high productive and high HI crop strains and improvements in both ECE and NUE. A great future challenge for agriculture will be to build on these achievements to maintain high efficiency and productivity without fossil-fuels.

Farm self-sufficiency is an asset against fossil fuels constraints, price volatility and greenhouse gas emissions of agriculture, however it inversely relates to farm surplus and is ultimately restricted by land availability which confines net production. Regaining energy and nitrogen self-sufficiency in agriculture could imply lower food exports to food deficit countries, less meat-rich diets or even the expansion of agriculture on conservation land such as forests. As a first approximation, the article suggests that agricultural self-sufficiency would bring down the farm surplus proportionally to the system's primary energy

requirements. This insight is a first step toward a more complete integration of the concept of self-sufficiency in prospective agricultural scenarios.

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