17èmes Journées de Recherches en Sciences Sociale, Paris-Saclay, 14 et 15 décembre 2023

VERSION PROVISOIRE – RESULTATS ENCORE EN COURS DE FORMULATION

La grande transition fossile de l'agriculture française : étude des transformations métaboliques associées à la spécialisation en grandes cultures du Bassin parisien, après 1945

Mathieu Maguet[1], Julia Le Noë[2]

(1) École Normale Supérieure Paris-Saclay, 91190, Gif-sur-Yvette, France.
(2) iEES, IRD, 75005, Paris, France.

Auteur de correspondance : mathieu.maguet@ens-paris-saclay.fr

Résumé. Ces dernières années, à l'interface des sciences biogéochimiques, de l'économie écologique et de l'histoire environnementale, on assiste à l'essor d'approches en termes de flux biogéochimiques, de métabolisme de matière et d'énergie, des évolutions historiques des sociétés industrielles et notamment de leur agriculture, passée en 150 ans de puits de carbone à émettrices de gaz à effet de serre. Ces recherches ont aussi pu mettre en lumière l'existence d'une émission nette de carbone des sols agricoles vers l'atmosphère compte tenu de la consommation d'énergie fossile directement liée à la production agricole (e.g., fertilisants de synthèse en azote, machines agricoles, importations de fourrages, etc…).

Dans la continuité de recherches déjà menées sur les métabolismes agricoles en France, l'objectif de cette communication sera d'analyser la dynamique socio-écologique des transformations métaboliques de l'agriculture dans le bassin parisien, plus précisément en Eure-et-Loir. Dans ce département, la spécialisation en grandes culture céréalière intensive en intrants carbonés fut particulièrement précoce, et la mécanisation fut rapide dans l'immédiate après-guerre.

Il s'agira dans un premier temps de donner à voir l'évolution des flux d'énergie dans le système agricole de 1929 à 2013, avec une attention particulière portée sur la période de fossilisation de l'agriculture entre 1945 et 1975. Cette analyse sera complétée par une évaluation de l'efficience énergétique de ces système agricole et une étude de son évolution dans le temps, tout en discutant des implications d'importants choix méthodologiques quand à son calcul. Dans un second temps, il s'agira d'analyser les logiques socio-politiques ayant façonné ces trajectoires biogéochimiques en s'appuyant sur un corpus bibliographique issu de l'économie politique, de l'économie rurale, de l'histoire des sciences et des techniques et de l'histoire environnementale.

Mots clés : Métabolisme – énergie – grandes cultures – Eure-et-Loir – machinisme agricole – EROI – modernisation agricole

The Great Fossil Transition of French Agriculture: Metabolic changes linked to the development of intensive field crop farming in the Paris Basin since 1945

Abstract. New works based on biogeochemical flows, energy and material metabolism, and studying the history of industrial societies are recently emerging at the intersection of biogeochemical science, ecological economics and environmental history. Some of those work focus especially on the history of agriculture, that switched in 150 years from carbon sink to greenhouse gas emitter. Those works showed for instance that agricultural lands are now net emitters of carbon to the atmosphere. This is caused by the fossil energy consumption in contemporary agricultural systems: synthetic nitrogen fertilizers, agricultural machines, feed imports, etc.

Building on previous works on agricultural metabolism in France, this paper examines the socio-ecological dynamics of the agricultural metabolism in the Paris Basin, more specifically in Eure-et-Loir. This *département* specialized early in intensive field crop farming relying on fossil fuels, and agricultural mechanization also started early after the Second World War.

We will first analyze the time series of energy flows in the agricultural system from 1929 to 2013, insisting especially on the 1945-1975 period that corresponds to the fossilization of agriculture. We will then estimate the energy efficiency of this agricultural system over time, while discussing the implications of the methodological choices made in computing this indicator. We will finally examine the socio-political dynamics that explain those biogeochemical trajectories using a corpus political economics, agricultural economics, science and technology studies, and environmental history.

Keywords: metabolism – energy – intensive field crop farming – Eure-et-Loir – agricultural machines – EROI – agricultural modernization

Classification JEL: N54 P18 Q19 Q49 Q56 Q57

1. Introduction: Energy in Agriculture

In most Western economies, agriculture now only represents a small share of GDP, including in France where it amounts to 2.1% in 2022[1]. Despite this, agriculture remains a crucial component in the basis of economies, and societies in general: indeed, to be able to work and produce economic value in other sectors, laborers need to be fed first. Agriculture is thus essential in allowing the division of labor, which allowed the "modern" civilization to exist. Among other things, like nutrients, food provides human beings with the energy needed for their continued existence, or "reproduction of their labor power" in Marxian terms. To sustain the rest of the economy, agriculture must then provide an *energy surplus* in the form of food, in addition to what it needs to reproduce the agricultural labor itself. This energy (or calorie) surplus of agriculture is ultimately what allows the division of labor and the existence of modern societies.

The energy surplus is thus a good marker of the role of agriculture in societies, but how to measure it? Agriculture does not only provide energy through food to the rest of the economy, but also requires inputs from it. Through those inputs, agriculture also requires energy from the rest of the economy, directly in the form of energy carriers such as fuel, or indirectly with inputs that required energy to be produced. Input-output models, developed by Leontief, allow to account for those two-way transfers between economic sectors in monetary terms. Similarly, the link between a sector and the rest of the economy can be studied in energy terms using an indicator called the *Energy Return On Investment* (EROI). For a given system exchanging with another, this indicator corresponds to the ratio of the usable energy delivered by the system to the energy provided to the system from the other one in order to obtain it. In a more concise way, the EROI corresponds to the ratio of energy outputs to energy inputs. If it is below 1, the system is a net consumer of energy, and it becomes a net provider of energy to the other system if it is greater than 1. In our case, the system is the agricultural sector, and the other system the rest of the economy. Agriculture also exchanges energy with the environment, mainly in the form of solar radiation captured through photosynthesis, but this energy being "free", i.e., available without any human work[2], it is not accounted for as an energy input to agriculture in the EROI (Aguilera et al. 2015, 5). Using the names of energy flows from figure 1, the definition of the EROI in the case of agriculture is:

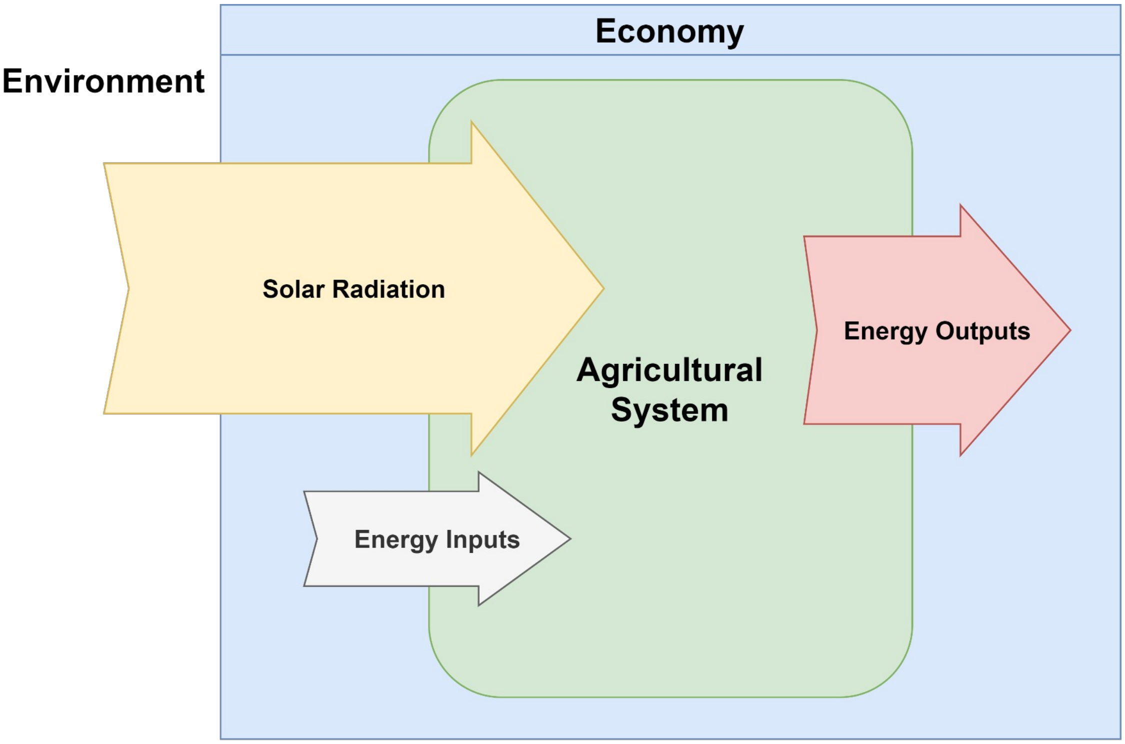
$$EROI = \frac{\text{Energy Outputs}}{\text{Energy Inputs}}$$

---

[1] This value also includes the wood and fishing industries. From "Valeur ajoutée par branche : Données annuelles de 1949 à 2022": https://www.insee.fr/fr/statistiques/2830197.

[2] Even though the solar energy is "free", its conversion in energy usable by humans by plant photosynthesis requires active anthropogenic action, which is in fact crop farming.

Figure 1: Main energy flows between agriculture, the rest of the economy, and the environment.



Source: own work.

Numerous studies compute the EROI of agricultural systems (Hercher-Pasteur et al. 2020), with different case studies and system boundaries. Several among them focus on the whole agricultural sector of a geographically defined system, like we are doing in this paper. Guzmán Casado and González de Molina (2017, chaps. 5–6) find that the EROI[3], both in the municipality of Santa Fe and in Spain, decreased between the beginning and the end of the 20th century. They confirmed those findings for Spain with a higher temporal resolution (2018). With the same indicators, Tello et al. (2016, table 2, p. 169) also find a decrease in the EROI from circa 1860 to 1999 in a small area of Catalonia (Spain). Studying two municipalities in Austria from 1830 to 2000, Gingrich et al. (2018, table 5, p. 945) found heterogeneous results, varying between the locations and computed indicators, and with changes in trends over time. Closer to our case study, Harchaoui and Chatzimpiros (2019, fig. 5b, p. 6) find that the EROI for France remained rather stable from 1882 to the 1950s, and then nearly doubled until 2013. The different case studies in these works may partly explain the heterogeneity in results, but a closer looks also reveals diverse methodological choices, that most likely play a significant role in explaining this heterogeneity. The review from Hercher-Pasteur et al. (2020) confirms the diversity of existing EROI indicators, as well as the differences in the evaluation of energy flows for identical dimensions of agricultural systems.

The state level studies, such as the one from Harchaoui and Chatzimpiros (2019), can possibly mask a high heterogeneity between regions within it. Le Noë et al. (2018) demonstrate this

---

[3] Guzmán Casado and González de Molina (2017) compute several EROI indicators in those chapters: the ones discussed here, that can be related to the indicators we are using, are the “final EROI” and “external final EROI”.

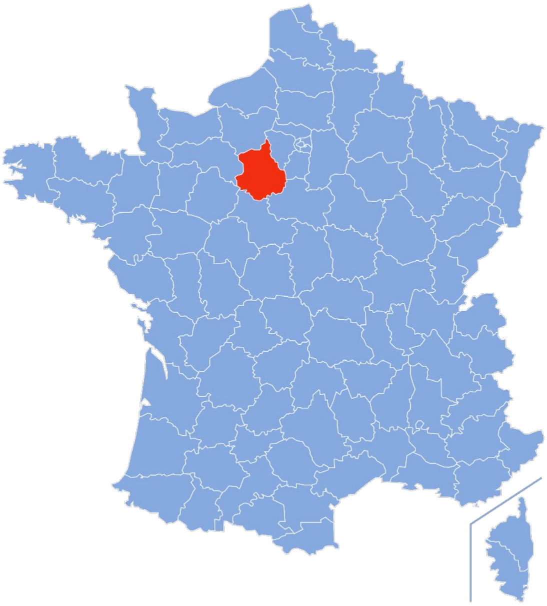
heterogeneity in the case of France, both through space and in the rhythm of change. To explore this heterogeneity, one must choose smaller geographical units, like regions or the French *départements*. To be able to link changes in energy flows and EROI to the economic, social and political phenomena that might explain them, it is valuable to evaluate energy flows and the EROI at a high time resolution. Computing the EROI for these smaller geographical units for only a handful of years – as Guzmán Casado and González de Molina (2017, chap. 5), Gingrich et al. (2018), and Tello et al. (2015) do – only allows to describe long-term changes and not to detect the effects of specific agricultural policies for instance. Yearly time series are ideal, but not always feasible because of data or research-time constraints.

The different methodologies used in computing the EROI can be related to different schools of thought, and more generally to different conceptual or political visions of agricultural systems. Despite their differences, those schools of thought have in common the concept of *metabolism*: a concept borrowed from biology that refers to the analysis of the physical (material and energy) flows between the economy and its environment, as well as within the economy. Those metabolic approaches correspond to different conceptual or political visions regarding the studied (economic) systems, and can in turn be related to different schools of thought in scientific ecology (Bahers 2021). Political ecology find its roots in Marxist thought, and with regard to agriculture, especially in the notion of "metabolic rift" between man and nature Foster (2000, 155–63). Social ecology usually promotes a long-term view relying on quantitative physical and economic indicators, and finds some roots in historical "Braudelian" approaches (from Fernand Braudel, a prominent member of the French *Annales* school), with a focus on socioeconomic structures (Fischer-Kowalski and Weisz 2016). Industrial ecology can be associated with environmental engineering, and sets out to evaluate the efficiency of the systems under study, often in order to find ways to "optimize" the flows, that is reducing resource consumption or improving recycling (Bahers 2021).

In this study, we explore different possibilities to compute the EROI and question: what are the political and conceptual implications of the associated methodological choices? What are the analytical consequences of those methodological choices, especially on the long-term trends? Can those methodological choices lead to contradicting EROI trends for the same case study?

Our case study is the Eure-et-Loir *département*, a mostly agricultural area South-West of Paris, specialized in large-scale crop farming (fig. 2). The agriculture in this area specialized early, compared to the rest of the French territory (Le Noë et al. 2018). Since the agricultural "modernization" in France happened mostly after the Second World War, our main study period starts in 1947. 1947 is the year at which the available statistical data are estimated to be reliable again, after the turmoil of the War. The end of our study period is 2013, the last year for which data on agricultural machines are available in agricultural statistics. The year 1929 is used as a reference for the pre-War situation, thanks to the trove of statistical data available for that year.

Figure 2: Location of the Eure-et-Loir département in France.



Source : Eure-et-Loir position by Marmelad/CC BY-SA.

2. Methods and Data

The nature of the energy for the flows included in the inputs and outputs when computing the EROI can vary. We follow the concepts used by Aguilera et al. (2015, 3) and Guzmán et al. (2014, 5). *Incorporated energy* corresponds to the higher heating value, or gross energy, of a material flow, that can be extracted from the matter itself. Note that this is different (and a bit higher than) the energy that can be metabolized by animals by ingesting the food or feed (if the matter is an agricultural product). *Energy requirements* correspond to the energy consumed for the production and delivery of a product or service (not necessarily material), that is not incorporated in the final product. Together, energy requirements and the incorporated energy (if it exists) form the *embodied energy* of a flow. Since nothing exists without a cause – at least for the systems we consider, let's skip the ontological discussions – evaluating the embodied energy of anything, especially its energy requirements, is an infinite recursion. With our worldly time constraints, we cannot hope to follow this infinite recursion, we thus have to define precisely what flows are evaluated and how. System boundaries, and the evaluation of the corresponding input and output flows are thus all methodological choices that will affect our (imperfect) EROI estimations.

2.1. Methodological Framework

2.1.1. System Boundaries

Since it relies on the energy inputs and outputs to and from a system, the calculation of the EROI depends strongly on the boundaries of the considered system. As such, defining clearly those boundaries is an essential matter in every EROI calculation and corresponds to important methodological choices.

Given the difficulties in estimating its energy consumption and our time constraints, the food industry that processes raw agricultural products is left out if the system. Since it is a further transformation step and every step degrades the energy efficiency of a process (from the second law of thermodynamics), the EROIs including the food industry would be lower than the ones we compute in this paper. The energy output is thus the final agricultural production, including both animal production and the share of vegetal production dedicated to feeding the population.

Regarding energy inputs, we try to take into account as much as possible the indirect energy consumption required to produce the agricultural inputs, thus including those industries in the system. However the labor force in those industries is difficult to evaluate and thus ignored. Given how energy intensive most of the industrial processes involved are – especially nitrogen fertilizer production (Smil 2004) – the energy cost of the workforce is probably much smaller than the other energy requirements of those industries.

The agricultural sector *per se* encompasses both crop and livestock farming. Draft animals are also considered within it, which means that their work is not considered as an energy input, and their feed is not part of the energy output. This is an important methodological choice, and one could make a different one: Harchaoui and Chatzimpiros (2019), for instance, consider draft animals as external to the system. Our choice is supported by the idea that those animals would not exist if they did not have the purpose of providing draught power. This is evidenced by the fact that they disappeared when machines replaced them as the main provider of power for agricultural work (in its physical sense here).

2.1.2. Specificity of Agricultural Labor

The position of agricultural workers with respect to the agricultural system is a major methodological choice when computing the EROI. If they are considered inside the system, one can (for the sake of simplicity) assume that they are consuming part of their own agricultural production; the corresponding incorporated energy is then subtracted from the agricultural output. If they are considered outside the system, they are just a share of the overall population who happen to use its labor force doing agricultural work. That is the choice made by Harchaoui and Chatzimpiros (2019) and the one we are making too. In contrast with draft animals, and assuming demography is not affected by agricultural regimes (which is simplifying, again), those workers would indeed still exist and still need food if they did not work in the agricultural sector. In this case, the energy required for their sustenance is part of the inputs of agriculture.

How to evaluate the energy required for the sustenance of agricultural workers is also an essential question. Most of the literature only considers the energy incorporated in the food required by these workers (Hercher-Pasteur et al. 2020, 10–11). The most comprehensive approach, informed by Marxian thought, would be to account for all the energy required in order to reproduce the labor force of workers over time. Intermediary approaches can be imagined: one could take the ratio of a total energy consumption corresponding to the working hours, or try to subtract the energy corresponding to leisure times for instance. In order to demonstrate the effect of this methodological choice on the EROI, we pick here two extreme approaches (regarding the amount of energy): either only the energy incorporated in food, or all the energy required for the reproduction of the labor force. Those two approaches are applied to Eure-et-Loir in section 3.3.

2.2. Estimating Energy Flows

Having defined the system boundaries and the flows to take into account, the problem that remains is estimating those flows, knowing all too well that perfectly capturing the embodied energy from all upstream processes is impossible.

Overall, the source data on agricultural production, and the quantities of each input (in terms of mass or number of units usually), come from agricultural statistics. We collected and assembled new data for this paper, but also relied on data already assembled by Le Noë (2018) and Le Noë et al. (2018). To evaluate the corresponding embodied energy, we use conversion factors from the scientific literature. For agricultural outputs, they are from Guzmán et al. (2014), and mostly from Aguilera et al. (2015) for inputs.

2.2.1. Output: Agricultural Production

We improved the time resolution of the dataset from Le Noë (2018) and Le Noë et al. (2018) to build yearly time series of agricultural production from 1969 on. This effort relied on databases extracted from the Agreste website, some being no longer available online and coming from personal communications (for 1969-1999). The conversion factors for incorporated energy are extracted from the supplementary materials of Guzmán et al. (2014) and assembled in the nomenclature used by Le Noë (2018).

2.2.2. Human Labor

As discussed earlier, we chose two estimates for the energy flow corresponding to human agricultural labor. In both cases, the source data is the number of agricultural workers. More precisely, we collected data on the number of full-time equivalents per year in agriculture, in order to account for part-time and seasonal work. This data is collected from the reports on the agricultural censuses from 1929, 1955, 1970, 1979, 1988, 2000, 2010 and 2020.

To evaluate the energy incorporated in the food the workers consume, we used the estimation of the carbon mass in average diets over time from Le Noë (2018), together with a standard conversion factor of 38MJ/kgC. To estimate the energy required for the reproduction of the labor force, we used as proxy the primary energy consumption per capita in France, taking into account both fossil fuel and electricity consumption (from other sources than fossil fuels).

2.2.3. Synthetic Fertilizers

We make use of the time series on synthetic nitrogen fertilizers consumption built by Le Noë (2018). Historicized conversion factors on their embodied energy are extracted from the supplementary materials of Aguilera et al. (2015).

Organic fertilizers such as manure are not taken into account since they are mostly produced by the agricultural sector itself, and are thus not an external input.

2.2.4. Agricultural Machines

Data on agricultural machines is provided by public agricultural statistics. Data on machine fleet was collected from reports published by the statistical office of the Ministry of Agriculture, every few years when available from 1947 to 2013, with the addition of 1929. The differing nomenclatures (tbl. 2 in appendix) were then aggregated to a common simple one.

The methodology for estimating the embodied energy of agricultural machines is heavily inspired from Aguilera et al. (2015). This methodology implies that the production energy requirements of agricultural machines are spread evenly over their whole estimated lifetimes, and not only accounted for on their production year. Historicized conversion factors are mostly extracted from the supplementary materials of Aguilera et al. (2015). Time series on the average machine power and annual hours of work in the French case provided by Harchaoui and Chatzimpiros (2019, S10, fig. S4-S5) are used in order to better localize our estimates.

This paper only makes use of embodied energy estimates for self-propelled machines: tractors and harvesters. Harvesters include combine harvester-threshers, but also forage harvesters and all self-propelled machines dedicated to harvesting crop. The fleet numbers for harvesters may include some tractor-drawn harvesters, since it was difficult to differentiate them from self-propelled ones with the available data.

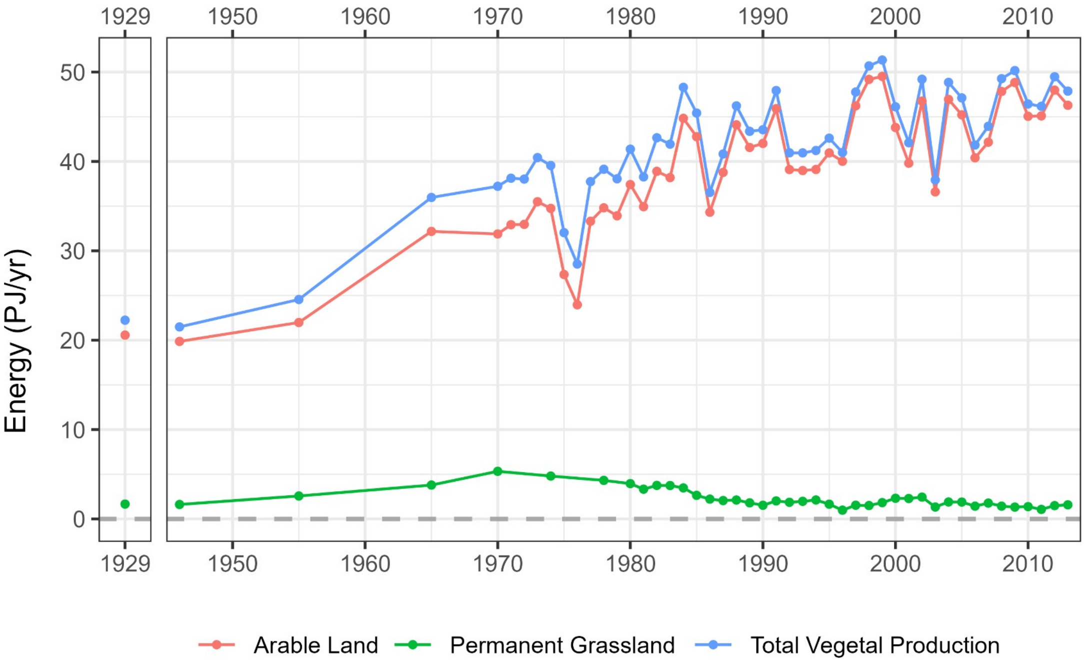
3. Preliminary Results

This work being still under way, this section will only present preliminary results. They hint at the results we will get at the end of this work, but can possibly change with the estimation of the remaining energy flows.

3.1. Agricultural Production

The specialization of Eure-et-Loir in large-scale crop farming appears clearly when comparing vegetal and animal production (figures 3 and 4): the vegetal production is much larger than the animal one for the whole period. The decrease of animal production since the mid-1950s, concurrently with an increase in vegetal production further illustrates this specialization. The doubling in vegetal production between 1929 and the 2000-2010s is also coherent with the agricultural “modernization” following the Second World War, and the associated productivity growth.

Figure 3: Energy incorporated in vegetal production in Eure-et-Loir[4]. It is not the vegetal output of the agricultural sector, since part of it is used internally as livestock feed. Straw is however already excluded since it is used internally, as livestock feed or bedding.

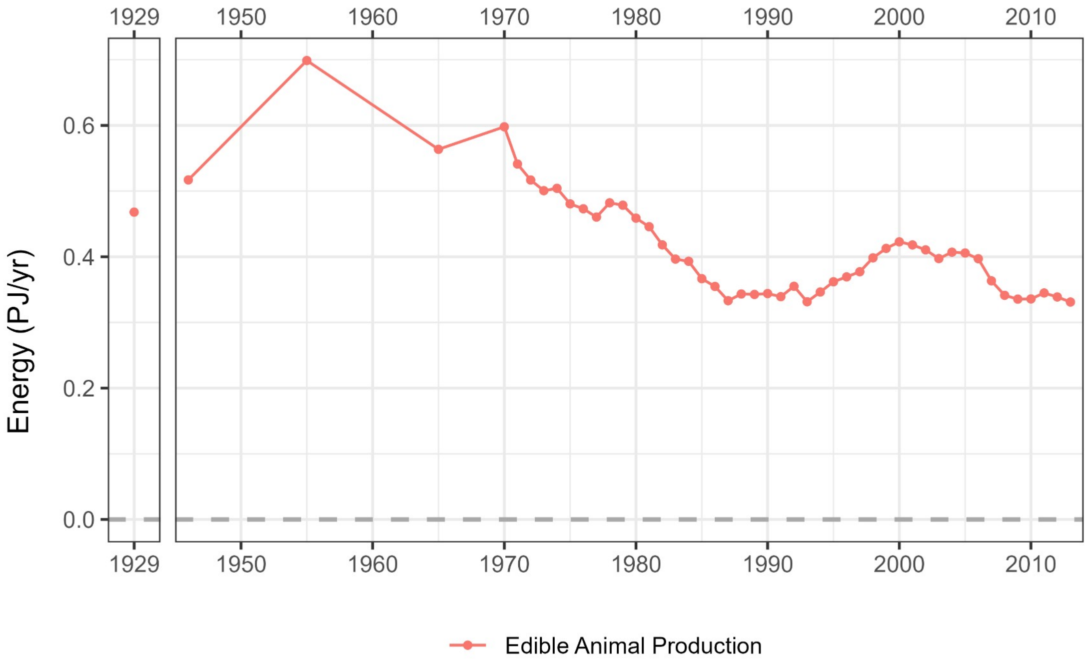


---

[4] In this figures and the following similar ones, the dots represent the years for which source data was collected. When a value aggregates several source values with different data availability, the dots were plotted according to the most important contributor to the aggregated values over the whole time period: wheat for vegetal production for instance. The values between the dots are obtained through linear interpolation, but since some energy conversion factors are historicized, the lines are not always straight between the dots. Historicized conversion factors are also linearly interpolated if not available for the whole time period.

The source for those figures is always "own calculations, from the sources cited in the Methods and Data section".

Figure 4: Energy incorporated in animal production in Eure-et-Loir.



3.2. Agricultural Inputs

3.2.1. Labor

The “modernization” of agriculture is also visible through the steep decrease in the volume of agricultural work (fig. 5): it was divided by nine from 1929 to 2013, and by eight from 1947.

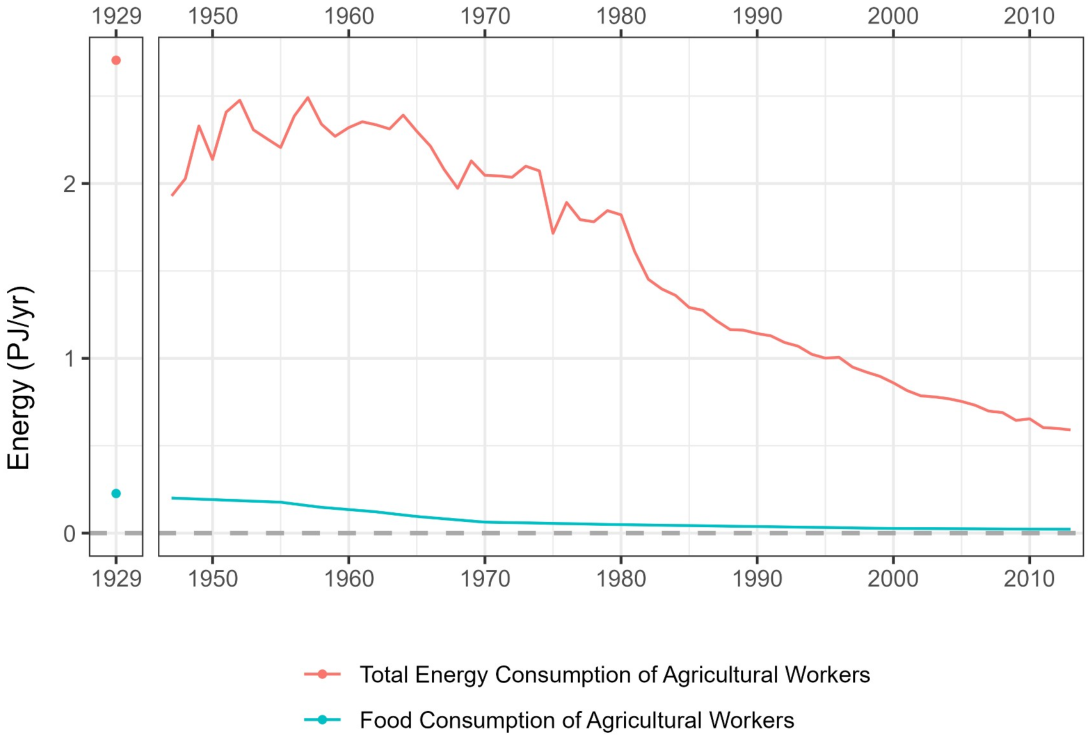
Figure 5: Labor volume in Eure-et-Loir over time, expressed in number of yearly full-time equivalents.

The energy corresponding to the average diet changed little over the period, from 5.0GJ/capita/year in 1929 to 4.3 in 2013. The energy incorporated in the diets of the agricultural workforce (fig. 6) thus follows the trend of the workforce itself.

Figure 6: Energy incorporated in the food consumed by agricultural workers in Eure-et-Loir.

The average energy consumption per capita nearly doubled from 1929 to 2013: from 60GJ/capita/year to 114. This trend contradicts the decreasing agricultural workforce. The total energy requirements for its reproduction were then only divided by around four between the beginning and end of the studied time period (fig. 7). This figure also highlights the discrepancy between the energy incorporated in food and the energy required for the reproduction of the labor force. Most EROI studies only consider the food requirements of the agricultural workforce (Hercher-Pasteur et al. 2020, 10–11).

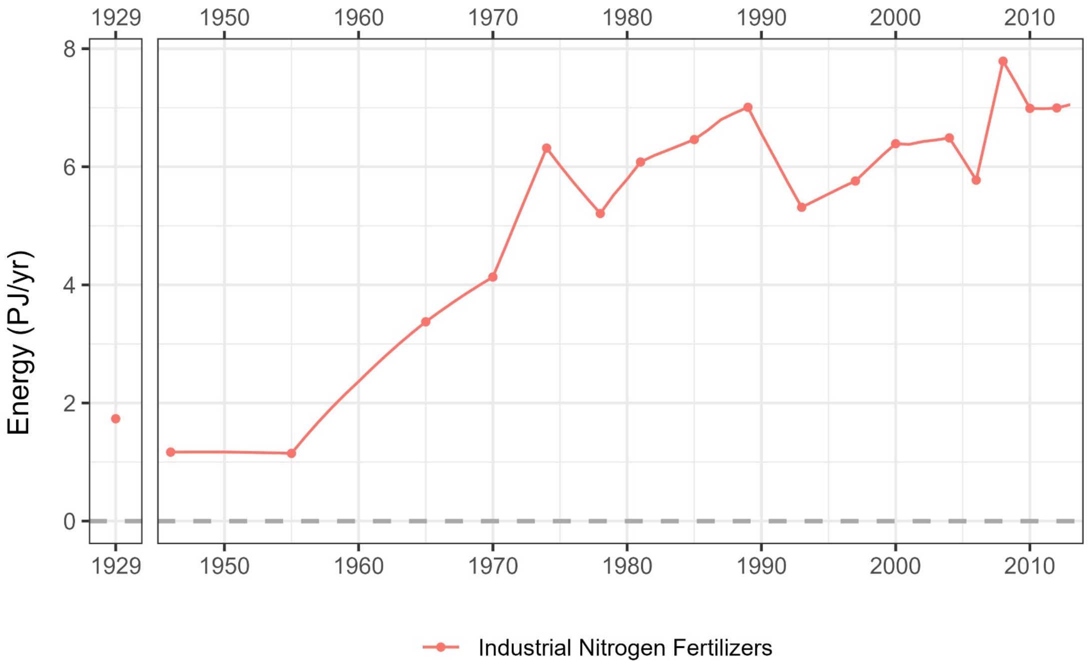
Figure 7: Total energy required for the reproduction of agricultural workers.



3.2.2. Synthetic Fertilizers

The agricultural “modernization” also translates into the growing use of fertilizers following the Second World War. The use of industrial nitrogen fertilizers increased ninefold from 1929 to 2013. The corresponding energy requirements only increased fourfold over the same period (fig. 8) since the energy intensity of nitrogen fertilizer production decreased from 166 to 73MJ/kgN.

Figure 8: Energy requirements for industrial fertilizers used in Eure-et-Loir.



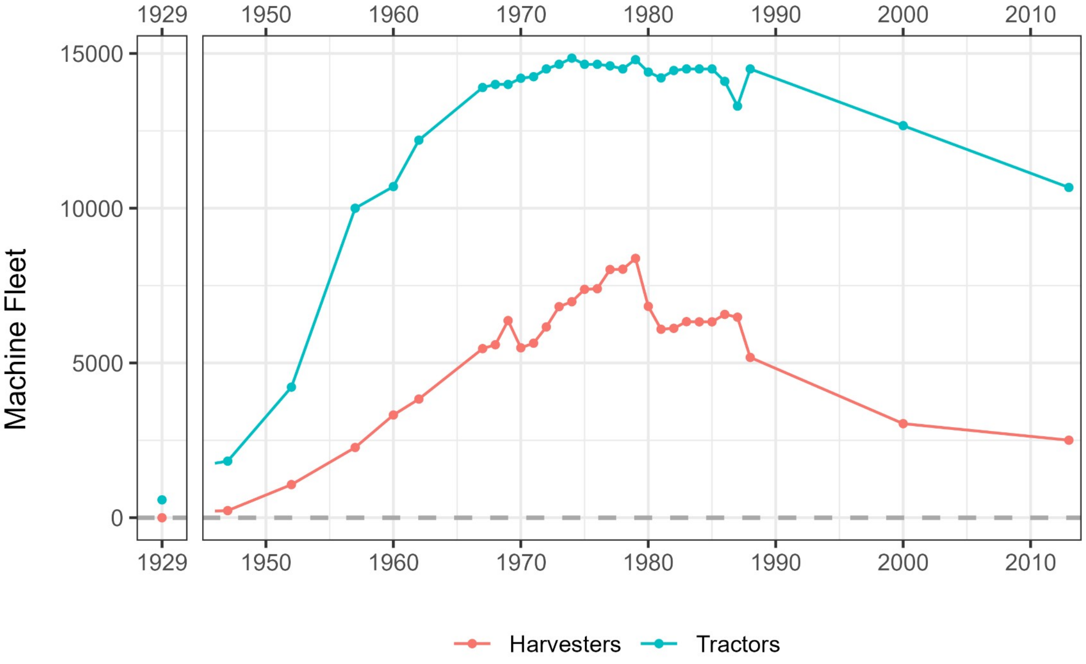
3.2.3. Agricultural Machines

As a perfect illustration of the mechanization of agriculture, the tractor fleet grew sevenfold in Eure-et-Loir between 1947 and the early 1970s (fig. 9). This steep increase started earlier than in France, where it happened mostly from the 1950s, and lasted until the beginning of the 1980s (Bonneuil, n.d.). This specificity of Eure-et-Loir can be seen as a consequence of its early specialization in large-scale crop farming (Le Noë et al. 2018). Eure-et-Loir was then probably an area where the initial equipment in large and powerful tractors in the years following the Second World War was quite significant, despite its quantitatively limited size at the national level (Bonneuil, n.d.).

Nearly all farms were probably equipped in tractors after this initial boom: there were 14200 tractors in Eure-et-Loir in 1970, for 10563 farms. This saturation of the market is a first explanation for the plateau reached by the tractor fleet in the 1970-1980s. From the end of the 1980s, the fleet starts decreasing, to reach 10671 tractors in 2013. The same pattern can be observed at the national level (Bonneuil, n.d.). This however does not correspond to a "de-mechanization": this decrease is caused by the concentration of land in ever fewer farms (Ansaloni and Smith 2021), with ever fewer agricultural workers (fig. 5). This trend, however, does not start in the 1980s: from 31394 farms in 1946, only 7940 remain in 1985, and 4318 in 2013. The plateau of the 1970-1980s is probably partially explained by that phenomenon too.

The self-propelled harvesters fleet was nearly non-existent in 1947, and grew steadily to reach a peak of 8380 in 1979, before decreasing to reach 2506 in 2013. The peak for harvester fleet arrives nearly a decade after the beginning of the plateau observed for tractors. This illustrates the standard equipment process of first buying a tractor, and only then investing in a harvester-thresher (Bonneuil, n.d.).

Figure 9: Fleet of self-propelling agricultural machines in Eure-et-Loir.



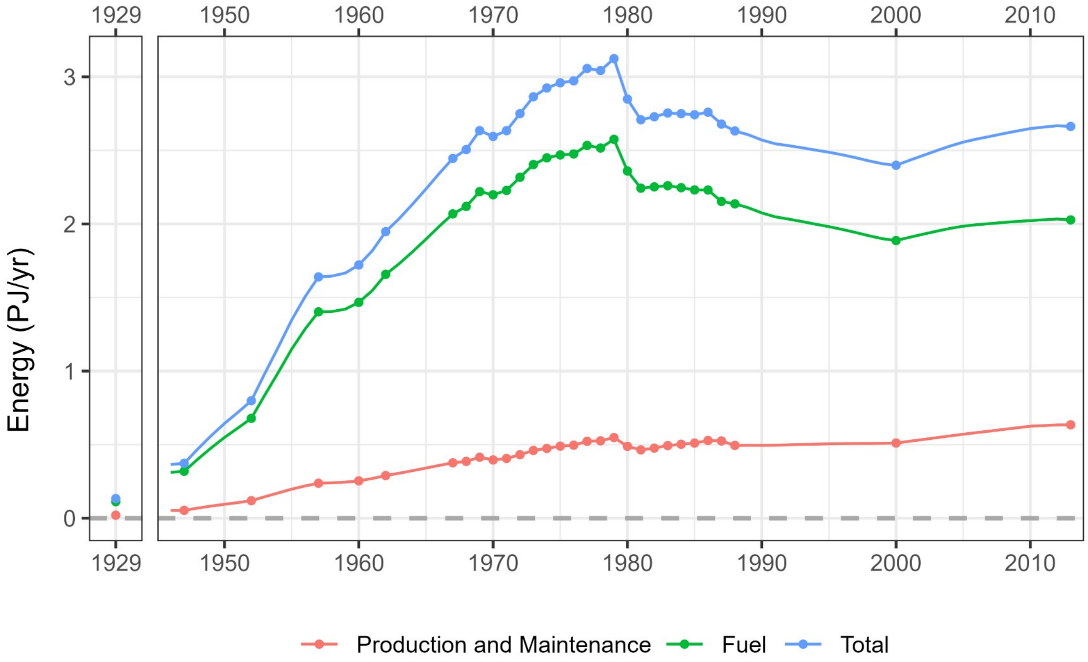
But how is it possible to cultivate the same agricultural area with ever less agricultural workers and machines (starting from a later year)? This apparent feat can be explained by the continuous increase in power (and size) of agricultural machines over the studied period (Bonneuil, n.d.; Harchaoui and Chatzimpiros 2019, fig. S4). Increased power and size should lead to higher fuel consumption and higher energy requirements for production.

The depletion of easily accessible reserves leads to decreasing energy efficiency for the extraction of most fossil energy carriers, and thus in increased embodied energy (Aguilera et al. 2015, 11–17). The improvements in motor efficiency and in the energy efficiency of most production processes, however, more than offset those losses. This leads to overall energy efficiency gains over the study period, for both fuel consumption and the energy embodied in machines during their production.

The changes in developments between the fleet (fig. 9) and the corresponding energy requirements (fig. 10) result from those two conflicting trends: bigger and more powerful machines on one side; energy efficiency gains on the other. The total energy requirements of agricultural machines grew more than sevenfold from 1947 to the early 1970s, similarly to the tractor fleet. This suggests that the increase in machine power were compensated by energy efficiency gains over this period. This initial growth persisted during the 1970s, while tractor fleet plateaued. It can probably be attributed in large part to the equipment of farms in harvesters that persisted during the 1970s. The energy requirements fell slightly between 1979 and 1981: this may be linked to the oil shocks of the 1970s, or simply to a statistical artifact regarding the harvester fleet. While the fleet in both tractors and harvesters declined since the 1980s, the corresponding energy requirements stayed more or less stable. It suggests that the continued increase in machine power compensated this declining fleet.

Most of the energy requirements of agricultural machines come from their fuel consumption (fig. 10). The energy embodied in fuel amounts for three quarters of these energy requirements in 2013, the remainder being the energy requirement for the production and maintenance of agricultural machines.

Figure 10: Energy embodied in agricultural machines and in the fuel they consume in Eure-et-Loir.



3.3. First EROI Estimates

These preliminary results allow to provide a first rough estimates of the planned EROI indicators, mostly to see the long-term trends that seem to appear. The vegetal production is used as a proxy of the total agricultural output. The actual output is smaller since livestock does not convert perfectly the energy incorporated in its feed in energy incorporated in animal products [Harchaoui and Chatzimpiros (2017)][5].

The first EROI indicators we are estimating are consistent with the definition of the agricultural sector excluding agricultural workers. They are not considered as a special part of the population, just as ordinary workers who happen to use their labor force doing agricultural work. The energy required for their work is thus only an energy input to the agricultural sector, since their food is

---

[5] We will be able to estimate the energy incorporated in livestock feed using the work done by Le Noë (2018) on carbon flows.

part of the global agricultural output that feeds the whole population (not only the local population since part of the production can be exported to other areas).

For the first EROI indicator – $EROI_1$ – only the energy incorporated in the food eaten by agricultural workers is accounted for. This is the methodological choice for most of the studies evaluating energy flows in agriculture (Hercher-Pasteur et al. 2020, 10–11).

$$EROI_1 = \frac{\text{Vegetal production}}{\text{Food consumption of agricultural workers} + \text{Synthetic nitrogen fertilizers} + \text{Agricultural machines}}$$

For the second EROI indicator – $EROI_2$ – all the energy needed for the reproduction of the agricultural labor force is accounted for.

$$EROI_2 = \frac{\text{Vegetal production}}{\text{Total energy requirements of agricultural workers} + \text{Synthetic nitrogen fertilizers} + \text{Agricultural machines}}$$

Table 1 presents the preliminary EROI estimates for these two EROIs for 1929 and 2013, computed using the above equations. In contrast to Harchaoui and Chatzimpiros (2019), that have a similar accounting methodology for human labor, $EROI_1$ decreases between 1929 and 2013. This decrease is caused by the superior increase of external inputs, relative to agricultural output. The difference with what Harchaoui and Chatzimpiros (2019) found comes mostly from them accounting for draught power as an agricultural input: a major input in 1929 that has nearly disappeared today.

Table 1: First EROI estimates for 1929 and 2013 and values used for their computation.
Source: own calculations, from the sources cited in the Methods and Data section.

Energy (PJ/yr)	**1929**	**2013**
Vegetal production	22.24	47.87
Food consumption of agricultural workers	0.23	0.02
Total energy requirements of agricultural workers	2.93	0.61
Synthetic nitrogen fertilizers	1.73	7.05
Agricultural machines	0.13	2.66
EROI	**1929**	**2013**
$EROI_1$	10.64	4.92
$EROI_2$	4.64	4.64[6]

---

[6] These identical values are not a mistake, they are obtained by rounding different results obtained with different calculations.

$EROI_2$, however, stays the same in 1929 and 2013 (but may change between those two years). This stability compared to $EROI_1$ can probably be explained by the important decrease in the total energy requirements for the reproduction of agricultural labor. Despite the doubling of the average energy consumption per capita, the collapse of the agricultural workforce led to a major decrease in the energy requirements of agricultural labor (figs. 5, 7), that compensated the growth of the energy requirement of other types of inputs (relative to the growing agricultural output).

Even if those results are only preliminary ones, they demonstrate the major effects of methodological choices regarding the EROI on its changes over time. These choices corresponding in turn to schools of thought and political standpoints, they must be clearly evidenced and their implications discussed. From a different standpoint, that can be justified as well, the energy efficiency improvement during the "modernization" of agriculture brought forward by Harchaoui and Chatzimpiros (2019) do not seem so indisputable. Depending on one's views of what is agriculture and what purpose it should serve, the results of quantitative studies and the derived recommendations for the future of the agricultural sector could change entirely.

References

Aguilera, Eduardo, Gloria I. Guzmán Casado, Juan Infante Amate, David Soto Fernández, Roberto García Ruiz, Antonio Herrera González de Molina, Inmaculada Villa, Eva Torremocha, Guiomar Carranza, and Manuel González de Molina. 2015. "Embodied Energy in Agricultural Inputs: Incorporating a Historical Perspective." Sociedad Española de Historia Agraria. Castelló de la Plana: Repositori Universitat Jaume I. https://repositori.uji.es/xmlui/handle/10234/141278.

Ansaloni, Matthieu, and Andy Smith. 2021. *L'expropriation de l'agriculture française : pouvoirs et politiques dans le capitalisme contemporain*. Dynamiques socioéconomiques. Vulaines sur Seine: Éditions du Croquant. https://editions-croquant.org/sociologie/735-l-expropriation-de-l-agriculture-francaise-pouvoirs-et-politiques-dans-le-capitalisme-contemporain.html.

Bahers, Jean-Baptiste. 2021. "Infrastructures et métabolisme urbain : luttes et enjeux politiques." *Terrestres* 20 (May). https://www.terrestres.org/2021/05/17/infrastructures-et-metabolisme-urbain-luttes-et-enjeux-politiques/.

Bonneuil, Christophe. n.d. "Pour une histoire de la grande transition fossile de l'agriculture française (années 1940-1973)." In *Politiques de la machine agricole : approches sociologiques et historiques des trajectoires de mécanisation [à paraître]*. Presses de l'ENS.

Fischer-Kowalski, Marina, and Helga Weisz. 2016. "The Archipelago of Social Ecology and the Island of the Vienna School." In *Social Ecology: Society-Nature Relations Across Time and Space*, edited by Helmut Haberl, Marina Fischer-Kowalski, Fridolin Krausmann, and Verena Winiwarter, 3–28. Human-Environment Interactions 5. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-33326-7_1.

Foster, John Bellamy. 2000. *Marx's Ecology: Materialism and Nature*. New York: Monthly Review Press. https://monthlyreview.org/product/marxs_ecology/.

Gingrich, Simone, Michaela Clarissa Theurl, Karlheinz Erb, and Fridolin Krausmann. 2018. "Regional Specialization and Market Integration: Agroecosystem Energy Transitions in Upper Austria." *Regional Environmental Change* 18 (4): 937–50. https://doi.org/10.1007/s10113-017-1145-1.

Guzmán Casado, Gloria I., and Manuel González de Molina, eds. 2017. *Energy in Agroecosystems: A Tool for Assessing Sustainability*. Advances in Agroecology. Boca Raton: CRC Press. https://doi.org/10.1201/9781315367040.

Guzmán, Gloria I., Eduardo Aguilera, David Soto Fernández, Antonio Cid, Juan Infante Amate, Roberto García Ruiz, Antonio Herrera González de Molina, Inmaculada Villa, and Manuel González de Molina. 2014. "Methodology and Conversion Factors to Estimate the Net Primary Productivity of Historical and Contemporary Agroecosystems." Sociedad Española de Historia Agraria. Castelló de la Plana: Repositori Universitat Jaume I. https://repositori.uji.es/xmlui/handle/10234/91670.

Guzmán, Gloria I., Manuel González de Molina, David Soto Fernández, Juan Infante-Amate, and Eduardo Aguilera. 2018. "Spanish Agriculture from 1900 to 2008: A Long-Term Perspective on Agroecosystem Energy from an Agroecological Approach." *Regional Environmental Change* 18 (4): 995–1008. https://doi.org/10.1007/s10113-017-1136-2.

Harchaoui, Souhil, and Petros Chatzimpiros. 2017. "Reconstructing Production Efficiency, Land Use and Trade for Livestock Systems in Historical Perspective. The Case of France, 1961." *Land Use Policy* 67 (September): 378–86. https://doi.org/10.1016/j.landusepol.2017.05.028.

———. 2019. "Energy, Nitrogen, and Farm Surplus Transitions in Agriculture from Historical Data Modeling: France, 1882." *Journal of Industrial Ecology* 23 (2): 412–25. https://doi.org/10.1111/jiec.12760.

Hercher-Pasteur, Jean, Eleonore Loiseau, Carole Sinfort, and Arnaud Hélias. 2020. "Energetic Assessment of the Agricultural Production System: A Review." *Agronomy for Sustainable Development* 40 (4): 29. https://doi.org/10.1007/s13593-020-00627-2.

Le Noë, Julia. 2018. "Biogeochemical Functioning and Trajectories of French Territorial Agricultural Systems : Carbon, Nitrogen and Phosphorus Fluxes (1852-2014)." PhD thesis, Sorbonne Université. https://tel.archives-ouvertes.fr/tel-02355318.

Le Noë, Julia, Gilles Billen, Fabien Esculier, and Josette Garnier. 2018. "Long-Term Socioecological Trajectories of Agro-Food Systems Revealed by N and P Flows in French Regions from 1852 to 2014." *Agriculture, Ecosystems & Environment* 265: 132–43. https://doi.org/10.1016/j.agee.2018.06.006.

Smil, Vaclav. 2004. *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production*. The MIT Press. https://mitpress.mit.edu/books/enriching-earth.

Tello, Enric, Elena Galán, Geoff Cunfer, Gloria I. Guzmán, Manuel González de Molina, Fridolin Krausmann, Simone Gingrich, et al. 2015. "A Proposal for a Workable Analysis of Energy Return on Investment (EROI) in Agroecosystems. Part I: Analytical Approach." *IFF Social Ecology Working Papers* 156: 1–110. https://upcommons.upc.edu/handle/2117/77586.

Tello, Enric, Elena Galán, Vera Sacristán, Geoff Cunfer, Gloria I. Guzmán, Manuel González de Molina, Fridolin Krausmann, et al. 2016. "Opening the Black Box of Energy Throughputs in Farm Systems: A Decomposition Analysis Between the Energy Returns to External Inputs, Internal Biomass Reuses and Total Inputs Consumed (the Vallès County, Catalonia, c.1860 and 1999)." *Ecological Economics* 121 (January): 160–74. https://doi.org/10.1016/j.ecolecon.2015.11.012.

Appendix

Table 2: Data sources and number of categories of agricultural machines available for each year. Note that not all those categories are used in our work.

Time period	Number of categories
1929	114
1947	20
1952	22
1957, 1960	20
1962	15
1967	19
1968	20
1969-1979 database	10
1980-1989 database	22
2000	7
2013	18